SIM PLANETQUEST
SCIENCE WITH THE SPACE INTERFEROMETRY MISSION

Project summaries contributed by
members of the SIM Science Team

Edited by Stephen Unwin and Slava Turyshev

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

SIM: PlanetQuest

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Contents

SIM - the Space Interferometry Mission - will perform precision optical astrometry on objects as faint as R magnitude 20. It will be the first space-based astrometric interferometer, operating in the optical band with a 10-m baseline. The Project is managed by the Jet Propulsion Laboratory, California Institute of Technology, in close collaboration with two industry partners, Lockheed Martin Missiles and Space in Sunnyvale, California, and TRW Inc., Space and Electronics Group in Redondo Beach, California. Launch of SIM is currently planned for 2009.

In its wide-angle astrometric mode, SIM will yield 4 microarcsecond (μas) absolute position and parallax measurements. Astrometric planet searches will be done in a narrow-angle mode, with an accuracy of 4 μas or better in a single measurement. As a pointed rather than a survey instrument, SIM will maintain its astrometric accuracy down to the faintest magnitudes, opening up the opportunity for astrometry of active galactic nuclei to better than 10 μas. SIM will define a new astrometric reference frame, using a grid of approximately 1500 stars with positions accurate to 4 μas.

The SIM Science Team was selected via a NASA Announcement of Opportunity, in November 2000. The Team comprises the Principal Investigators of ten Key Projects, and five Mission Scientists contributing their expertise to specific areas of the mission. Their science programs cover a wide range of topics in Galactic and extragalactic astronomy. They include: searches for low-mass planets - including analogs to our own solar system - the formation and dynamics of our Galaxy, calibration of the cosmic distance scale, and fundamental stellar astrophysics. All of the science observing on SIM is competitively awarded; the Science Team programs total about 40% of the total available, and the remainder will be assigned via future NASA competitions.

This report is a compilation of science summaries by members of the Science Team, and it illustrates the wealth of scientific problems that microarcsecond-precision astrometry can contribute to. More information on SIM, including copies of this report, may be obtained from the project web site, at `http://sim.jpl.nasa.gov`.

Stephen Unwin and Slava Turyshev

Editors

The Search for Young Planetary Systems And the Evolution of Young Stars

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The Space Interferometer Mission (SIM) will provide a census of planetary systems by conducting a broad survey of 2,000 stars that will be sensitive to the presence of planets with masses as small as $\sim$ 15 Earth masses (1 Uranus mass) and a deep survey of $\sim$ 250 of the nearest stars with a mass limit of $\sim$ 3 Earth masses. The broad survey will include stars spanning a wide range of ages, spectral types, metallicity, and other important parameters. Within this larger context, the Young Stars and Planets Key Project will study $\sim$ 200 stars with ages from 1 Myr to 100 Myr to understand the formation and dynamical evolution of gas giant planets.

The SIM Young Stars and Planets Project will investigate both the frequency of giant planet formation and the early dynamical history of planetary systems. We will gain insight into how common the basic architecture of our solar system is compared with recently discovered systems with close-in giant planets by examining 200 of the nearest (<150 pc) and youngest (1-100 Myr) solar-type stars for planets. The sensitivity of the survey for stars located 140 pc away is shown in the planet mass-separation plane (Figure 1).

We expect to find anywhere from 10 (assuming that only the presently known fraction of stars, 5-7%, has planets) to 200 (all young stars have planets) planetary systems. We have set our sensitivity threshold to ensure the detection of Jupiter-mass planets in the critical orbital range of 1 to 5 AU. These observations, when combined with the results of planetary searches of mature stars, will allow us to test theories of planetary formation and early solar system evolution.

By searching for planets around pre-main sequence stars carefully selected to span an age range from 1 to 100 Myr, we will learn at what epoch and with what frequency giant planets are found at the water-ice "snowline" where they are expected to form. This will provide insight into the physical mechanisms by which planets form and migrate from their place of birth, and about their survival rate. With these data in hand, we will provide data, for the first time, on such important questions as: What processes affect the formation and dynamical evolution of planets? When and where do planets form? What is initial mass distribution of planetary systems around young stars? How might planets be destroyed? What is the origin of the eccentricity of planetary orbits? What is the origin of the apparent dearth of companion objects between planets and brown dwarfs seen in mature stars?

The observational strategy is a compromise between the desire to extend the planetary mass function as low as possible and the essential need to build up sufficient statistics on planetary occurrence. About half of the sample will be used to address the "where" and "when" of planet formation. We will study classical T Tauri stars (cTTs) which have massive accretion disks and post- accretion, weak-lined T Tauri stars (wTTs). Preliminary estimates suggest the sample will consist of $\sim$ 30% cTTs and $\sim$ 70% wTTs, driven in part by the difficulty of making accurate astrometric measurements toward objects with strong variability or prominent disks. The second half of the sample will be drawn from the closest, young clusters with ages starting around 5 Myr, to the 10 Myr thought to mark the end of prominent disks, and ending around the 100 Myr age at which theory suggests that the properties of young planetary systems should become
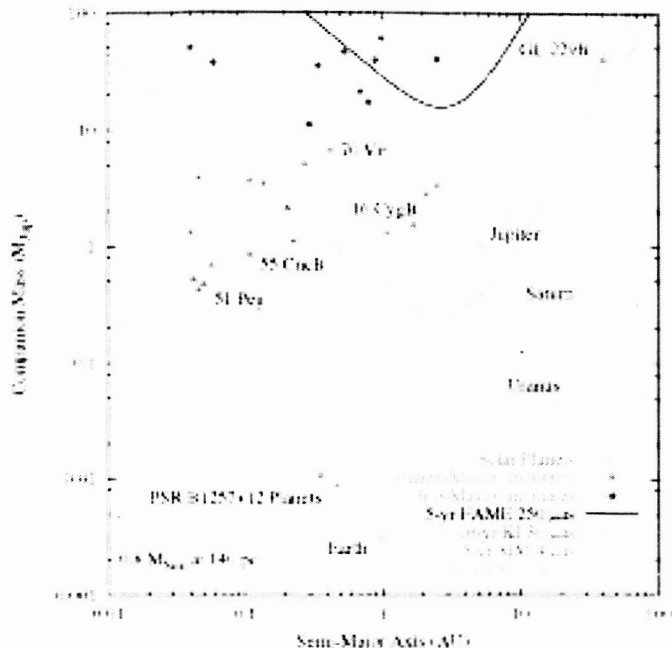
Figure 1: Comparison of our SIM survey, FAME, and the Keck Interferometer for the detection of planets around young stellar objects at a distance of 140 pc. We adopt single measurement accuracies of 4 μas for SIM, 250 μas for FAME (both for 5 yr missions), and 30 μas for the Keck-Interferometer (10 yr mission). We also show the sensitivity to planets for 30 m/s radial velocity measurements appropriate for young stars (10 yr survey).

indistinguishable from those of mature stars. The properties of the planetary systems found around stars in these later age bins will be used to address the effects of dynamical evolution and planet destruction (Lin et al. 2000).

The sample will consist mostly of stars in well known star-forming regions 125-140 pc away but will also include stars such as those in the TW Hydrae Association which are only 50 pc away. Only single stars meeting stringent requirements on photospheric stability, lack of nebulosity, and absence of a strong gas disk will be included in the sample. Such stars offer the stable photo-center needed for accurate astrometry. With proper selection, the effect of various astrophysical disturbances can be kept to less than a few μas.

A secondary goal of the program is put our knowledge of stellar evolution on a firmer footing by measuring the distances and orbital properties of $\sim$ 100 stars precisely enough to determine the masses of single and binary stars to an accuracy of 1%. This information is required to calibrate the pre-main sequence tracks that serve as a chronometer ordering the events that occur during the evolution of young stars and planetary systems

SIM's census of planetary systems will address fundamental questions about the properties of planetary systems and the existence of terrestrial planets around the closest stars. The Young Star Key Project will provide the data needed to understand the formation and evolution of solar systems and address whether systems like our own are common or rare in the solar neighborhood.

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Discovery of Planetary Systems With SIM

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We are witnessing the birth of a new observational science: the discovery and characterization of extrasolar planetary systems. In the past five years, over 70 extrasolar planets have been discovered by precision Doppler surveys, most by members of this SIM team. We are using the data base of information gleaned from our Doppler survey to choose the best targets for a new SIM planet search.

In the same way that our Doppler database now serves SIM, our team will return a reconnaissance database to focus Terresrial Planet Finder (TPF) into a more productive, efficient mission.

Goals

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

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

3. Determine absolute masses of Doppler-detected planets and search for additional planets

4. Determine the degree of coplanarity in known multiple systems

5. Reconnaissance for TPF

While our proposed science projects assume 1 μas precision, in every case, we have inherent flexibility to select different targets that will accommodate the ultimate operating precision of SIM.

Current Knowledge About Extrasolar Planets

- The level of giant-planet occurrence (0–2 AU): 7%

- The rising nature of the mass function down to current detection threshold (1 M_{SAT})

- Eccentric orbits are common (due to scattering?).

- There exist multiple systems of giant planets.

Discovery Space for Extrasolar Planets
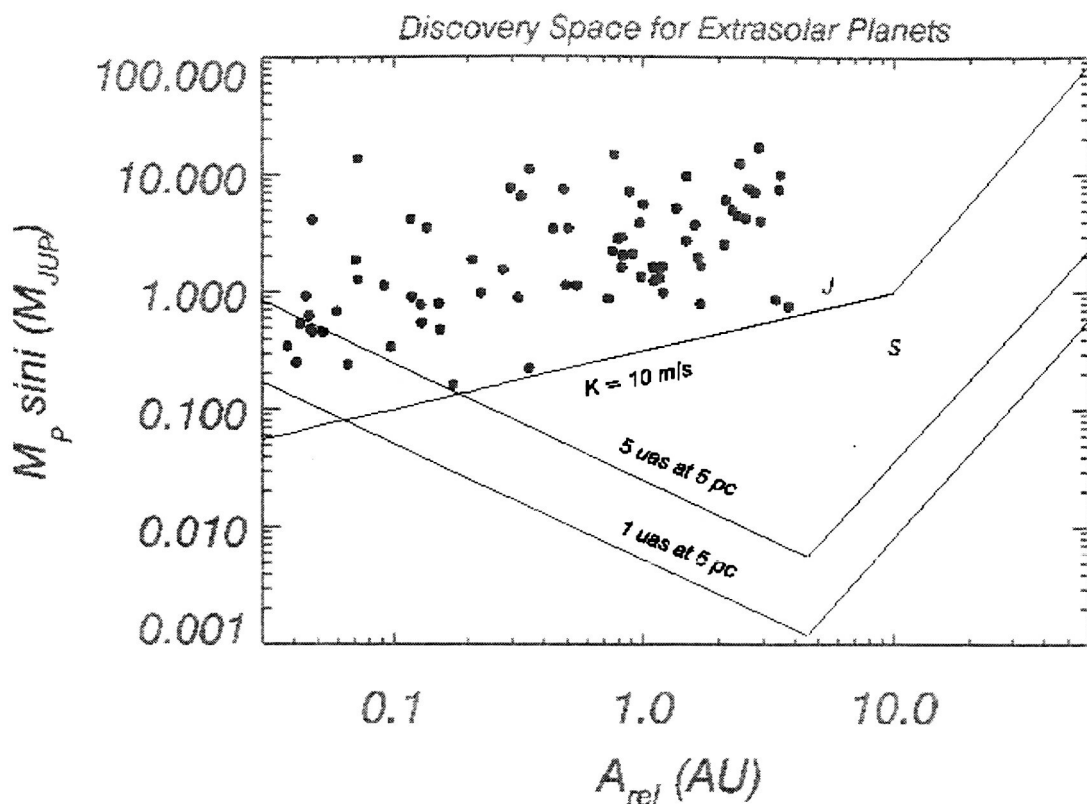
Figure 1: Detectable Parameters: SIM will detect planets that are 3 M_{Earth} or more massive in the habitable zone around nearby stars. High-precision Doppler work will be used to identify the best SIM targets: stars with habitable zones that could harbor dynamically stable Earths.
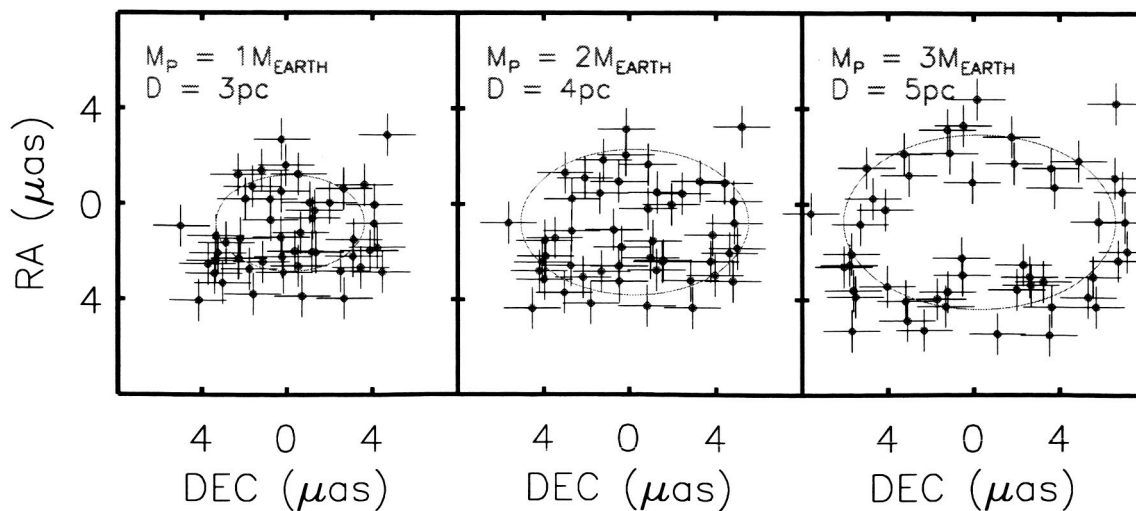
Figure 2: Ultraprecise Planet Search: 1 μas Precision. High-cadence SIM observations of a few well studied, nearby stars could reveal planets of a few earth masses.

Current Ignorance About Extrasolar Planets

- The occurrence rate and mass distribution of terrestrial planets

- The architecture of planetary systems

- Eccentricities of low-mass planets

- The occupancy rate of the habitable zone

Our SIM planet search is designed to answer key questions about the cosmic properties of planets in general. What fraction of stars have planetary systems? How many planets are there in a typical system? What is their distribution of masses and semimajor axes? How common are circular orbits? How commonly do planetary systems have an architecture similar to that of our Solar System?

Properties of planets below 1 M_{SAT} may be estimated speculatively from known higher mass planets by extrapolation, the only estimate available. The rising mass function implies that a significant fraction, perhaps 30–50% of all single stars, will harbor planets of mass, $M = 10$ M_{Earth} – 1 M_{SAT}, detectable by SIM. Indeed, many (most?) will harbor multiple planets in that mass range. Our SIM planet search must be designed to anticipate the astrometric confusion stemming from multiple planets.

In addition, orbital eccentricities are ubiquitous within 2 AU for Jupiter-mass planets. It remains unknown whether terrestrial planets will also exhibit eccentric orbits. Clearly, therefore, a SIM planet search must obtain enough observations per star to adequately assess the often subtle eccentricity parameters.

We are compiling years-long plots of precision Doppler measurements for each SIM target star. This Doppler reconnaissance of all SIM target stars establishes the saturns and jupiters within 3 AU, and provides Doppler suggestions of 10–30 M_{Earth} planets. We consider this Doppler reconnaissance of SIM targets to be a prerequisite of a SIM planet search. Many planets with Neptune-Saturn-Jupiter mass will be anticipated and included in SIM astrometric models.

We are currently surveying the nearest 900 G,K, and M main sequence stars in the northern hemisphere with the Lick 3-m and the Keck 10-m telescopes. We are also surveying the nearest 200 GK southern hemisphere stars with the Anglo-Australian 3.9-m telescope. Moreover, with the 6.5-m Magellan telescope, we will extend our Doppler reconnaissance to another 600 GKM stars in the southern hemisphere. From the Doppler reconnaissance (both detections and nondetections), ideal SIM targets will be chosen, as described in section 4. Indeed, by the time of the SIM launch, we project that 200 jupiter–saturn planets will be known, with hints of dozens of planets from 10-30 M_{Earth} within 1 AU.

Narrow Angle Reference Stars

To maximize SIM's astrometric accuracy, we are employing Doppler techniques to compile a network of reference stars. These reference stars must be:

- astrometrically stable to 1 μas

- located within a 0.5 degree radius in order to achieve 1 μas precision

- brighter than V = 12 to minimize the exposure times.

The existence of a sufficient number of reference stars must be one of the selection criteria for science target stars. Hence the focus of studies before SIM's launch date will be the identification of a reference grid around each of the targets selected from the Doppler program.

The optimal stars to serve as local reference stars are K giants. Because of their bright intrinsic luminosity, K giants can be found at greater distances than almost any other star of the same apparent magnitude. Hence, they offer the smallest astrometric jitter from dynamical effects (e.g., planets and stellar companions) compared to other stars of the same apparent magnitude. With a typical brightness of $V = 11.5$ at 2 kpc, K giants are plentiful enough to provide several candidate reference stars for most science targets. Indeed, we consider K giants to be the only objects suitable to serve as narrow angle reference stars.

Every known star closer than 5 pc of F,G,K,M spectral type is already being observed in our surveys. Since these stars constitute targets for which the highest astrometric precision is desired, we will increase our ground-based monitoring (both sampling frequency and S/N) in order to obtain the highest precision Doppler reconnaissance for planetary companions. The candidate reference stars to the 5 pc sample should also be observed at the higher Doppler precision.

A detection of a terrestrial planet will be extremely challenging because the amplitude of the signal is so low. Figure 2 shows simulations of astrometric data for a 1 M_{Earth} planet at 3 pc, a 2 M_{Earth} planet at 4 pc, and a 3 M_{Earth} at 5 pc. In these simulations, as in all other simulations shown in this proposal, the data are plotted as if the parallax and proper motion were known and cleanly removed. In fact, absolute parallaxes may not be known for these stars unless the reference stars are modeled as grid stars, so the astrometric perturbations due to orbital motion will actually be tiny wobbles on top of enormous signals.

Extrasolar Planet Inferometric Survey (EPIcS)

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The discovery of the nature of the solar system was a crowning achievement of Renaissance science. The quest to evaluate the properties of extrasolar planetary systems is central to both the intellectual understanding of our origins and the cultural understanding of humanity's place in the Universe; thus it is appropriate that the goals and objectives of NASA's breakthrough Origins program emphasize the study of planetary systems, with a focus on the search for habitable planets. We propose an ambitious research program that will use SIM—the first major mission of the Origins program—to explore planetary systems in our Galactic neighborhood. Our program is a novel two-tiered SIM survey of nearby stars that exploits the capabilities of SIM to achieve two scientific objectives: (i) to identify Earth-like planets in habitable regions around nearby Sun-like stars; and (ii) to explore the nature and evolution of planetary systems in their full variety. The first of these objectives was recently recommended by the Astronomy and Astrophysics Survey Committee (the McKee-Taylor Committee) as a prerequisite for the development of the Terrestrial Planet Finder mission later in the decade. Our program combines this two-part survey with preparatory and contemporaneous research designed to maximize the scientific return from the limited and thus precious observing resources of SIM.

Our first objective demands measurements with the highest possible astrometric accuracy ($\sim 1~\mu$as) and thus requires long observing times for each target. Thus a survey addressing only this objective should focus on relatively few (~ 75) nearby stars. In contrast, our second, broader objective is best accomplished with reduced astrometric accuracy ($\sim 4~\mu$as) and shorter integration times, allowing us to survey thousands of stars of many different types throughout a larger volume. We have juggled SIM's operational constraints to develop an optimized hierarchical observing strategy capable of achieving both objectives in a single, coordinated survey. The survey is designed to hedge our bets in the face of the current near-total uncertainty in the frequency and diversity of planetary systems. Our strategy virtually guarantees important and exciting scientific returns regardless of whether planetary systems like our own are typical features of most stars or rare and precious ornaments.

We will use SIM for a two-tiered Extrasolar Planet Interferometric Survey (EPIc survey, or EPIcS). The *Tier 1* survey is designed primarily to address our first objective, the detection of Earth-like planets around nearby stars. The Tier 1 targets will consist of ~ 75 main-sequence (MS) stars within 10 pc of the Sun. About a third of these will be G dwarfs resembling the Sun; this sample is large enough that even the absence of terrestrial planets would be an extremely significant—if discouraging—result. The remainder of the Tier 1 targets will be inactive MS stars of other spectral types: mostly K and M, but including ~ 10 A and F stars to provide a preliminary survey of planets around young, massive stars. The *Tier 2* targets will consist of ~ 2100 stars from the following diverse classes: all MS spectral types, in particular early types; binary stars; stars with a broad range of age and metallicity; stars with dust disks; evolved stars; white dwarfs; and stars with planets discovered by radial-velocity surveys. Each class addresses specific features of the planet-formation process (are metals necessary for giant planet formation? does the number of planets decline slowly with time due to dynamical evolution? what is the

relation between dust disks and planets?), and will contain >100 targets to ensure that our findings are statistically robust.

The observing strategy is crafted for maximum efficiency and accuracy. We will observe each Tier 1 target $\sim$ 70 times over the course of the mission, with each observation comprised of $\sim$ 20 1-min integrations (10 each on a science target and a reference) that will be averaged to provide astrometry with $\sim$ 1 μas accuracy. Within the 15° radius Field of Regard (FOR) associated with each Tier 1 target, we will identify $\sim$ 28 Tier 2 targets that are bright (R $<\sim$ 12), and usually within 25 pc. We will observe Tier 2 targets with single 1-min integrations, aiming for $\sim$4 μas accuracy. This "piggybacking" of Tier 2 observations on Tier 1 pointings saves pointing overhead, provides some redundancy within each FOR, and decreases the systematic errors in Tier 1 observations. We also propose a preparatory research program to maximize the scientific return from our survey, involving both target selection and the development of analysis pipelines. An important aspect of this program is the focus on identifying stable reference stars in each Tier 1 FOR, and developing analysis software that can handle the complications introduced by possible acceleration of the reference stars.

Our preparatory program includes radial velocity (RV) and adaptive optics (AO) imaging observations to help us select the best science targets and reference stars. For science targets, the main goal of these observations is to ensure that the targets do not have companion stars that would preclude the existence or detection of low-mass planets. For reference stars, the goal is to identify one or two reference stars within 1.5° of each Tier 1 target (Tier 2 targets can use more distant grid stars as references). We will study two classes of candidates: bright ($\sim$ 10 mag) MS stars in binary systems (chosen to have orbits that scour out any planets that could complicate the astrometry)and distant K giants at a distance of 1 Kpc. Because we can't rule out the possibility of planetary companions to K giants, two references are needed to unambiguously assign a planet to the target or one of the reference stars.

To maximize the return from SIM, we must analyze complex and scarce astrometric data with the highest possible reliability and efficiency. Traditional tools such as the Lomb-Scargle periodogram (LSP) and its variants must be sharpened. We have already created new methods that promise significant improvements over the LSP. A goal of our preparatory research is to have a tunable data analysis pipeline before mission start implementing a variety of methods for such tasks as delay calibration, planet detection, and estimation of orbital parameters.

Once the mission is underway, we anticipate that significant analytical and observational work will be needed to supplement the SIM observations. We will undertake important parts of this research ourselves, but also will adopt a policy of early data release to focus the attention and resources of the community on SIM and on extrasolar planets, to encourage independent analysis, to receive suggestions for revisions in our observing and sampling strategy, and to display our progress in time to justify an extended mission.

A MASSIF Effort To Determine
The Mass-Luminosity Relation For Stars of
Various Ages, Metallicities, and Evolution States

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The MASSIF (Masses and Stellar Systems with Interferometry) Team will use SIM to investigate the mass content of the Galaxy — from huge stars to barely glimmering brown dwarfs, and from hot white dwarfs to exotic black holes. We will target various samples of the Galactic population to determine and relate the fundamental characteristics of mass, luminosity, age, composition, and multiplicity — attributes that together yield an extensive understanding of the stars. Our samples will include distant clusters that span a factor of 5000 in age, and commonplace stars and substellar objects that lurk near the Sun.

Mass is the most fundamental characteristic of a star. It governs a star's entire evolution — determining which fuels it will burn, what color it will be, and how long it will live. It is crucial to our understanding of stellar astrophysics that we determine stellar masses to high accuracy. Knowing the masses of main sequence stars answers basic stellar astrophysics questions such as, *What is the biggest star? How is the mass of a stellar nursery partitioned into various types of stars?* and, *What is the mass content of the Galaxy and how does it evolve?* In fact, the dependence of luminosity upon mass — the mass-luminosity relation (MLR) — is one of the few stellar relations sufficiently fundamental to be applicable to many areas of astronomy. With the exception of the H-R Diagram, it is the single most important "map" of stellar astronomy.

The principal goals of the MASSIF Key Project are to (1) define the mass-luminosity relation for main sequence stars in five fundamental clusters so that effects of age and metallicity can be mapped (Trapezium, TW Hydrae, Pleiades, Hyades, and M67), and (2) determine accurate masses for representative examples of nearly every type of star, stellar descendant, or brown

dwarf in the Galaxy. To reach these goals we will measure masses with errors of 1% or less for roughly 200 stars, which will allow us to challenge stellar astrophysics models more severely than ever before. There are currently only ~40 stars with masses this accurately known, and 30 of those are components in eclipsing binaries with masses between 1 and 3 $M_\odot$. Thus, the range of our understanding of precise stellar masses is terribly limited. SIM can rectify this situation because it has the capability to measure precisely the largest known mass for a star, as well as the smallest known mass for a brown dwarf. The extrema of the H-R Diagram will receive intense scrutiny so that we can understand just where the stellar main sequence begins and ends. We will also investigate exotic targets such as supergiants and black holes to further our understanding of these rare but intriguing objects. In the process of carrying out this investigation, we will develop a well-stocked "toolbox" of mass-luminosity relations at optical and infrared wavelengths that can become the standards against which all stars are measured.

An important consequence of our program will be accurate masses for stars that have extra-solar planets. SIM will not "see" planets — it will only measure the effects that planets have on their host stars. Even when combined with high-precision radial velocity data, an estimate of the star's mass is required to derive the mass of the planet. Our ensemble of mass-luminosity relations will allow accurate estimates for the masses of stars with extrasolar planets, and consequently, accurate estimates for the planet masses.

In addition, because the proposed observations will target 100 or more relatively close binary systems (separated by tens of AU or less), a search for planets in those systems will be carried out. Currently, we have no understanding of planetary survival in stellar binaries that have separations similar to our solar system. Thus, through the MASSIF effort, perhaps we can finally answer the question, *Is it possible to have two nearby Suns hanging in the sky of a world?*
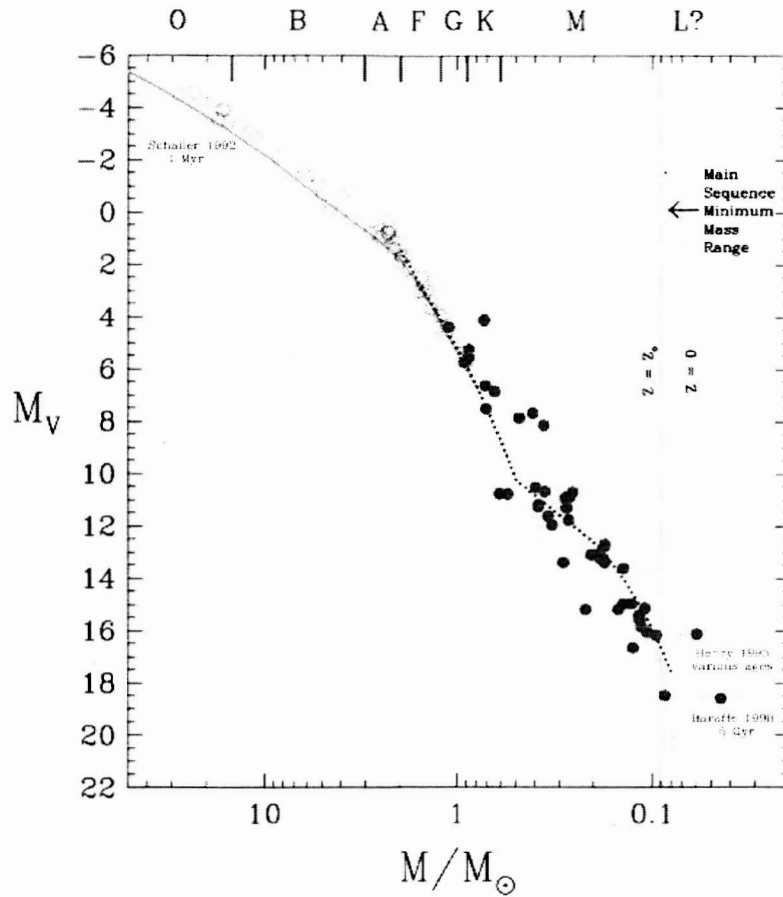
Figure 1: The Mass-Luminosity Relation at optical wavelengths for field stars is shown. Masses from 30 $M_\odot$ to 0.08 $M_\odot$ are represented by open points for eclipsing binaries and solid points for astrometric binaries. The region from 0.092 and 0.072 $M_\odot$ marks the minimum main sequence mass range for objects with zero to solar metallicity. Three fits are shown — model fits for massive stars from Schaller *et al* (1992) and for low mass stars from Baraffe *et al* (1998), and empirical fits (dotted line) from Henry & McCarthy (1993) and Henry *et al* (1999). Each fit has a terminus near 1 $M_\odot$.

Anchoring the Population II Distance Scale: Accurate Ages for Globular Clusters

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The metal-poor stars in the halo of the Milky Way galaxy were among the first objects formed in our Galaxy. These Population II stars are the oldest objects in the universe whose ages can be accurately determined. Age determinations for these stars allow us to set a firm lower limit to the age of the universe and to probe the early formation history of the Milky Way. The age of the universe determined from studies of Population II stars may be compared to the expansion age of the universe and used to constrain cosmological models. The largest uncertainty in estimates for the ages of stars in our halo is due to the uncertainty in the distance scale to Population II objects. We propose to obtain accurate parallaxes to a number of Population II objects (globular clusters and field stars in the halo) resulting in a significant improvement in the Population II distance scale and greatly reducing the uncertainty in the estimated ages of the oldest stars in our galaxy. At the present time, the oldest stars are estimated to be 12.8 Gyr old, with an uncertainty of $\sim15\%$. The SIM observations obtained by this key project, combined with the supporting theoretical research and ground based observations outlined in this proposal will reduce the estimated uncertainty in the age estimates to 5%.

The expansion age of the universe is determined by the present expansion rate of the universe (given by the Hubble constant, H_0), the matter density of the universe (parameterized by Ω_M) and the vacuum energy density of the universe Ω_Λ. Astronomy is entering into an era of precision cosmology where these fundamental cosmological constants will soon be determined to an unprecedented accuracy from a variety of ground and space based observations. These SIM key project observations and resultant age determination for the universe will provide an important, independent check of the preferred cosmological model.

The ages we determine will also be used to probe the early formation history of the Milky Way. Understanding the process of galaxy formation is a key quest in astrophysics and is one of the long term goals of NASA's Origins Program. The Milky Way plays a unique role in furthering our understanding of galaxy formation as it is the only large galaxy for which we can obtain detailed chemical, kinematic, and chronology information. The Milky Way provides us with a fossil record of its formation period, which yields unique insights into the process of galaxy formation.

RR Lyrae variable stars are Population II standard candles and can be used to determine the distances to globular clusters and nearby galaxies beyond the reach of SIM. An important part of this key project will be to determine the luminosity of the RR Lyrae stars. This will be done via distance determinations to globular clusters rich in RR Lyrae stars and a selected sample of RR Lyrae stars in the field. This calibration of the luminosity of RR Lyrae stars will allow accurate distances to be obtained to a number of distant globular clusters and nearby galaxies (such as the Large and Small Magellanic Clouds). Refining the distance estimates to nearby galaxies will help calibrate the zero point of the extragalactic distance scale.

In order to achieve these goals, the following SIM observations will be obtained:

1. Parallax and proper motion measurements to 5 stars in each of 21 different globular clusters. These clusters have been chosen to span a range in metallicities, horizontal branch types, number of RR Lyrae stars and Oosterhoff type

2. Parallax measurements to a selected sample of 60 field RR Lyrae stars, chosen to complement the RR Lyrae star observations taken by FAME

3. Parallax and proper motion measurements to 60 metal-poor main sequence turn-off and subgiant branch stars in the field, allowing us to determine the age of the halo stars and directly compare this to the globular clusters ages.

Field stars make up about 99% of the halo, and are an important population to study in our quest to understand the early formation history of the Milky Way. The parallaxes we obtain for a large sample of main sequence turn-off and subgiant branch stars in the halo of the Milky Way will allow us to accurately determine the ages of these stars and will complement our globular cluster age estimates in providing a firm lower limit to the age of the universe.

To take full advantage of the SIM parallax results will require a concentrated effort to reduce other uncertainties associated with the age determination process. Accurate photometry and heavy element abundances will be obtained for all of the target stars and globular clusters. Helium abundances will be determined through studies of eclipsing binaries in the nearest globular clusters and double-lined spectroscopic binaries in the halo. We will also undertake detailed spectroscopic studies for stars in selected globular clusters to establish a very high quality set of gf values, and apply those results to determine the atmospheric parameters and [Fe/H] values for all of our program clusters and field stars. We will obtain the even more crucial abundances of oxygen and other elements for all of our targets. We will seek to reduce possible systematic errors by using a variety of oxygen lines in stars in selected clusters. The resultant high-precision chemical compositions will be used as input parameters to the stellar models and isochrones. The input physics used to construct the theoretical stellar models and isochrones will be improved through a continuing investigation of the fundamental physics which governs the evolution of stars. These ground based observations and theoretical work are key to substantially reducing the error in age estimates for the oldest stars in the Galaxy.

This investment will lead to an improved understanding of the galaxy formation process, a substantially improved Population II distance scale and an determination of the minimum age of the universe to an accuracy of 5%.
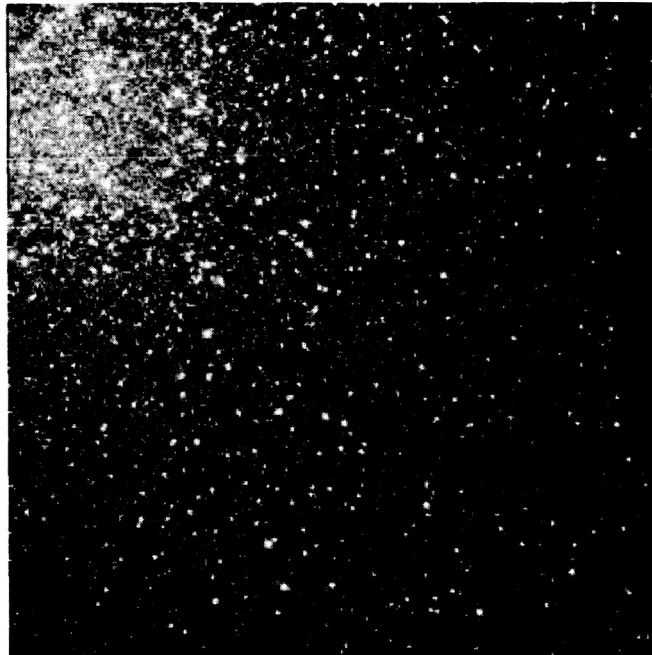
Figure 1: HST picture of a portion of the globular cluster 47 Tucanae (from R. Gilliland). This SIM key project will determine the parallax to this cluster to an accuracy of 2%, allowing the age to be determined with an accuracy of 6%.

Taking Measure of the Milky Way

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We intend to use SIM to make definitive measurements of fundamental structural and dynamical parameters of the Milky Way. The important niche in dynamical parameter space afforded by SIM can be exploited to resolve, with unprecedented precision, a number of classical problems of Galactic astronomy. In addition, we have developed new tests of the Galactic mass distribution specifically designed for data with the special properties of SIM products. Our proposed suite of experiments will utilize the SIM Astrometric Grid as well as complementary observations of star clusters and other strategically-selected, distant "test particles" for a definitive characterization of the major components (bulge, disk, halo, satellite system) of the Milky Way.

Specifically, our goals will be:

1 . The determination of two fundamental parameters that play a central role in virtually every problem in Galactic astronomy, namely

   (a) the solar distance to the center of the Milky Way, R_0

   (b) the solar angular velocity around the Galactic center, ω_0

2. The measurement of fundamental dynamical properties of the Milky Way, among them

   (a) the pattern speed of the central bar

   (b) the rotation field and velocity-dispersion tensor in the disk

   (c) the kinematics (mean rotational velocity and velocity dispersion tensor) of the halo as a function of position

3. The definition of the mass distribution of the Galaxy, which is dominated by the presence of dark matter. We intend to measure

   (a) the relative contribution of the disk and halo to the gravitational potential

   (b) the local volume and surface mass density of the disk

   (c) the shape, mass and extent of the dark halo of the Milky Way out to 250 kpc

Although we have divided the Key Project into several distinct projects, these projects are closely related and cannot be solved in isolation. For example, an accurate measurement of the Oort limit strongly constrains models of the spatial distribution of mass in the disk and the total mass of the inner halo, while an accurate determination of R_0 and Θ_{LSR} is needed to interpret the phase-space distribution of halo tracers and the kinematics of tidal tails. While the proposed SIM observations are meant specifically to address the definition of the fundamental structure and

dynamics of the Galaxy, they also permit substantial inroads into numerous ancillary problems regarding stellar populations and the evolution of the Milky Way.

To the greatest extent possible, we will take advantage of the data already being obtained for sub-solar metallicity K giants in the SIM Astrometric Grid. These data, produced as part of the mission's baseline operations, will be supplemented by SIM observations of other targets, among them:(1) counterparts to the Astrometric Grid stars at greater distances, (2) a sample of disk Mira and Cepheid variables, (3) a sample of disk open clusters, (4) the brightest few stars in every Galactic globular cluster and satellite dwarf galaxy, and (5) stars in tidal tails of disrupted satellite galaxies and globular clusters.

While the primary goal of our Key Project is focused on the global spatio-dynamical properties of the Milky Way, and this goal dictates strictly the selection of our intended targets, we also intend to address the wealth of information these data will yield on Galactic stellar populations and the insight provided into the formation history of the Milky Way. Therefore, we intend to supplement the astrometric data with ground-based observations of abundances, radial velocities, and other properties, to maximize the benefits of the SIM data for analyses of stellar populations.
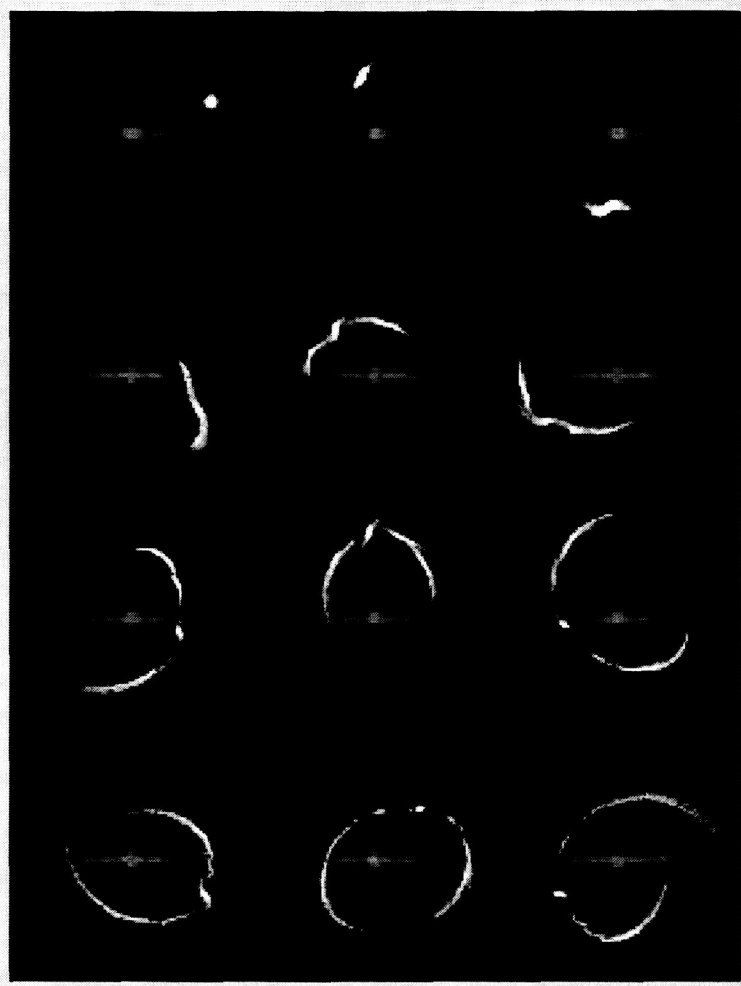
Figure 1: These images are taken from a simulation by K. V. Johnston of a satellite being torn apart by the Milky Way's tidal field. The simulation followed the satellite's evolution for several billion years. The Milky Way is represented in blue in the center, with the yellow satellite orbiting around it. The satellite itself appears much larger than it really is in these animations because the images were.colored to emphasize the density of the stars being stripped from the satellite. We plan to use SIM to measure accurate proper motions of stars in the tidal debris streams of several Milky Way dSph satellites as a precise means to measure the Galactic potential as a function of radius in the halo.

Stellar, Remnant, Planetary, and Dark-Object Masses from Astrometric Microlensing

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Introduction: A Galactic census

The primary goal of our project is to make a complete census of the stellar population of the Galaxy. We are broadening the term "stellar" here to include both ordinary stars and dark stars. Ordinary stars, burning their nuclear fuel and shining, can perhaps best be studied with traditional astronomical techniques, but dark stars, by which we include old brown dwarfs, black holes, old white dwarfs, neutron stars, and perhaps exotic objects such as mirror matter stars or primordial black holes, can only be studied by their gravitational effects. Traditionally, these objects have been probed in binaries, and thus selected in a way that may or may not be representative of their respective field populations.

The only way to examine the field population of these stars is through microlensing, the deflection of light from a visible star in the background by an object (dark or not) in the foreground. When lensed, there are two images of the background star. Although these images cannot be resolved when the lens has a stellar mass, the lensing effect can be detected in two ways: photometrically, i.e. by measuring the magnification of the source by the lens, and astrometrically, i.e. by measuring the shift in the centroid of the two images.

Photometric microlensing experiments have detected hundreds of microlensing events over the past decade. Despite its successes, photometric microlensing has so far been somewhat frustrating because these events are difficult to interpret. Almost nothing is known about the masses of individual lenses and very little is known about the statistical properties of the lenses treated as a whole, such as their average mass. Although probably over 100 of the lenses are in fact dark objects, we can't determine which they are, let alone investigate finer details such as what their masses are, and where they are in the Galaxy.

With SIM, we will break the microlensing degeneracy, and allow detailed interpretation of individual microlensing events. We will thus develop a detailed census of the dark and luminous stellar population of the Galaxy.

Breaking the microlens degeneracy

The difficulty in interpretation is due to the microlensing degeneracy. Each microlensing event is determined by three parameters, the lens-source relative parallax and proper motion, and the mass of the lens. Unfortunately, in the vast majority of events today, we can only measure one physical parameter, the event time scale, which is related to these three. This microlensing degeneracy makes any individual event impossible to interpret, and also stymies most of the interpretation of a statistical sample of events.
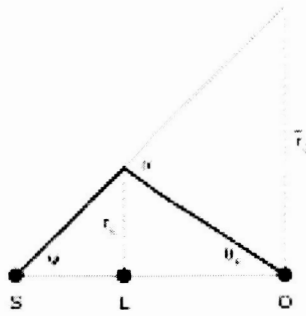
Figure 1: Illustration of the two key parameters that SIM will measure: the Einstein angle, θ_E which is the displacement of the image from the true position of the source, "S", as observed from the Earth, "O", and the projected Einstein radius, $\tilde{r}E$, which describes the characteristic distance an observer would have to move to see a significant change in the lensing event. If we can measure these observables, we can determine all physical features of the lens, "L". For the vast majority of microlensing events, neither of these parameters can be measured from the ground, but both can be measured with SIM.

First note from Fig. 1 that, using the small angle approximation, $D_l = \tilde{r}E/\alpha = r_E/\theta_e$. Hence,

$$\theta_E\tilde{r}E = \alpha r_E = \frac{4G}{c^2}M \tag{1}$$

Where we have made use of the Einstein light-deflection formula $\alpha = 4GM/r_Ec^2$. That is, the mass is completely determined from the product of θ_E and $\tilde{r}E$.

How can one measure these two parameters? The Einstein angle, θ_E is roughly the difference between the position of the two images of the source when lensed and its true position. Thus, in principle it could be measured by simply comparing the positions of the images during the lensing event with the source postion after the event. Even SIM will not be able to resolve the two images of the source. However, one of the two images will be brighter than the other, and the centroid of light of the two blended images will be shifted slightly from the true position of the source towards the brighter image during the lensing event, typically by about 100 μas. With its 4 μas precision, SIM will be able to accurately measure this shift, and so θ_E.

To measure $\tilde{r}_E$, we can imagine a vast array of telescopes distributed around the solar system, each searching for photometric microlensing, the magnification of a source star by the lens. Only those telescopes within $\tilde{r}_E$ (typically a few AU) of the point perfectly aligned with the source and the lens will see any magnification. In practice, only two telescopes are needed, one on Earth, and one elsewhere in the solar system. From the difference in the event as seen by these two telescopes, one can reconstruct $\tilde{r}E$. Since SIM will be in a trailing solar orbit, moving away from the Earth at 0.1 AU/yr, SIM photometry (a byproduct of its astrometric observations) can be used to determine $\tilde{r}E$ in this manner.

Thus, using the unique capabilities of SIM, its μas astrometry and its solar orbit, we will be able to completely solve the event and measure the mass, location, and speed of the lens.

Using this method, we will learn what and where are the stellar components of the Galaxy, in the disk, the bulge, and the halo.

The Galactic mass function

The present day mass function of luminous objects is reasonably well determined, but that of dark objects is totally unknown. A Monte Carlo realization of how SIM will measure the combined
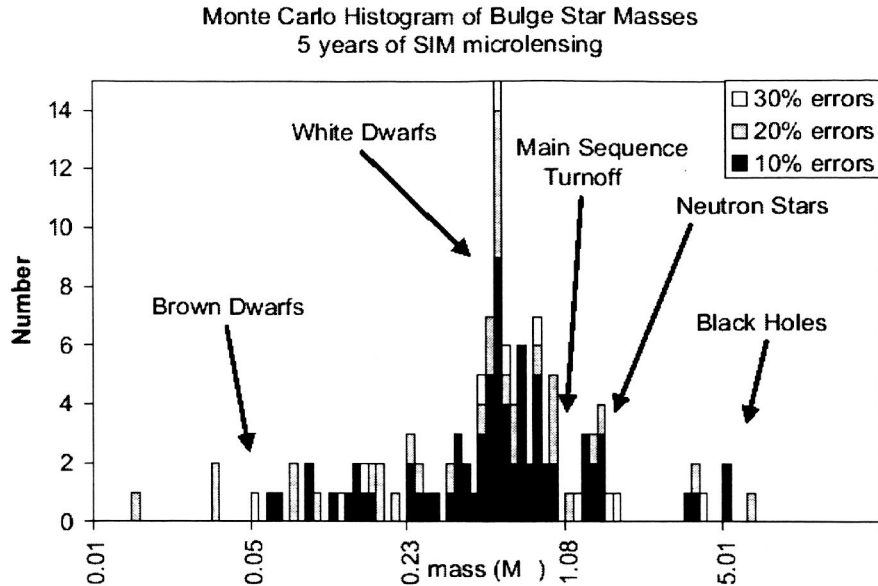
Figure 2: A Monte Carlo realization of how SIM will measure the combined mass function using astrometric microlensing.

mass function using astrometric microlensing is shown in Fig. 2. Notice that it has several interesting features. There are distinct bumps for various different stellar remnant populations: white dwarfs, neutron stars, and black holes. The contributions of these dark objects to the mass of the Galaxy will be uncovered, as will some details of their individual mass functions.

The mass function is determined over two orders of magnitude in mass: we can study the initial mass function of stars well below the hydrogen burning limit, which will allow us to probe a possible brown dwarf cuttoff. Any kinks, breaks, or other features will be real, not due to any theoretical mass-luminosity-age relation. These features will give clues to star formation, and a comparison between the bulge mass function and the local mass function will help determine the effect of metallicity and environment on star formation.

Since the Galactic bulge is generally considered a proxy for old spiral bulges and ellipticals, a detailed understanding of its MF (including both dark and luminous stellar objects) will provide essential insight into these systems which contain the majority of the stellar mass in the universe. The bulge MF cannot be measured over this mass range by any other proposed technique, whether ground-based or space-based.

In addition to the mass of the lens, we will also be able to measure its distance and transverse velocity. Whereas in the past, using purely photometric microlensing, we were merely able to say that there was a lens somewhere along the line of sight, we will now be able to sort each lens by Galactic component as well as by mass, leading to further insights into the structure of the Galaxy.

Nature of the Dark Halo

The original motivation for the past decade of microlensing research was to determine whether the dark halo is composed of discrete lumps of mass, massive compact halo objects (MACHOs). Current results by the MACHO collaboration find a microlensing optical depth towards the LMC

consistent with 20% of the mass of the halo being composed of MACHOs, an order of magnitude greater than could be caused by any known stellar population.

This result has defied simple explanation, leading to a number of proposed, but somewhat strained explanations. Either the lenses *are* in fact in the halo, in which case, they must be some exotic object (ordinary dark lenses such as white dwarfs and brown dwarfs have been ruled out), or the lenses must be in or near the LMC. Resolving this dilemma requires determining the location of the lens.

The location of the lens is bedevilled by the same degeneracies discussed above. Of the tens of lenses observed towards the Magellanic Clouds, only two lenses have been conclusively located, both in the SMC, and these two lenses are unique in several ways and may not be representative of the lensing population as a whole. Fortunately, SIM can determine the location of the lenses in a similar manner as the mass of the lens. From Fig. 1 and the exterior angle theorem:

$$\frac{\theta_E}{\tilde{r}E/\mathrm{AU}} = AU\left(\frac{\alpha}{\tilde{r}E} - \frac{\psi}{\tilde{r}E}\right) = \frac{\mathrm{AU}}{D_l} - \frac{\mathrm{AU}}{D_s} \equiv \pi_{\mathrm{rel}}. \tag{2}$$

where $\pi_{\mathrm{rel}} = \pi_l - \pi_s$ is the lens-source relative parallax. Lenses in the halo should have a large π_{rel}, lenses in the magellanic clouds will have a negligible π_{rel}. We will measure π_{rel} for five magellanic cloud lenses. If all five have negligible π_{rel} then we will know that the lensing is due to ordinary stars around the Magellanic Clouds. If some or all of the lenses have a measurable π_{rel}, then we will know that a substantial part of the mass of the Galaxy is made of some exotic objects.

Masses of nearby stars

In a distinct, but related experiment, astrometric microlensing of nearby stars provides an alternate route to measuring stellar masses with high accuracy. We have examined catalogs of proper motions stars to determine when nearby stars will pass in front of a more distant star, close enough to allow a measurable deflection of its light. By measuring this deflection with SIM, we will determine the mass of the nearby star to 1% accuracy.

Astrometric microlensing nicely complement traditional measurements of the masses of nearby stars. First, it works by a completely different physical principle than the standard methods. It will be especially useful in uncovering any systematic errors in the traditional mass measurements. Second, it works for single stars (and components of binaries with much wider separations than visuals), and can thus test whether or not binarity has any effect on the mass of stars. Third, the selection bias is toward high proper-motion (hence low-metallicity, [Fe/H] ~ -2) stars. At present, no low metallicity stars have accurate mass measurements.

Conclusion

With SIM, we will be able to measure the deflection of light by individual stars. We will thus be able to break the microlensing degeneracy and measure the mass, distance, and velocity of the lens. SIM thus opens up a new method of surveying the Galaxy, determining what objects are where, how many, and of what mass, irrespective of whether those objects are bright stars in the bulge, white dwarfs in the disk, or dark matter candidates in the halo. Astrometric microlensing with SIM will measure the masses of nearby stars by a new technique that is competative with and complementary to the traditional method of observing binary stars.

Binary Black Holes, Accretion Disks and Relativistic Jets: Photocenters of Nearby AGN and Quasars

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Team Members:
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One of the most challenging questions in astronomy today is to understand the origin, structure, and evolution of the 'central engines' in the nuclei of quasars and active galaxies (AGNs). The favoured theory involves the activation of relativistic jets from the fueling of a supermassive black hole through an accretion disk. In some AGN an outer optically thick, 'dusty torus' is seen orbiting the black hole system. This torus is probably related to an inner accretion disk - black hole system that forms the actual powerhouse of the AGN. In radio-loud AGN two oppositely-directed radio jets are ejected perpendicular to the torus/disk system.

Although there is a wealth of observational data on AGN, some very basic questions have not been definitively answered. The Space Interferometry Mission (SIM) will address the following three key questions about AGN.

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

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

3. Do the cores of galaxies harbour binary supermassive black holes remaining from galaxy mergers? It is not known whether such mergers are common, and whether binaries would persist for a significant time.

Astrometry of quasars The SIM fringe spacing is ≈ 10 milliarcseconds (mas), so most AGN cores will be unresolved. However, with global astrometry, radio (ICRF) and optical (SIM) positions of radio-loud quasars can be compared at the sub-milliarcsecond level. Changes in the optical positions over the course of the mission will be resolvable by SIM at the few μas level. Such changes may be caused by motion of relativistically beamed features in a jet. In addition to absolute astrometry, SIM will allow differential astrometry – color-dependent position shifts – across the optical waveband. This will prove to be a powerful diagnostic tool for AGN structure on scales of a few μas.

Testing AGN models using astrometry SIM should be able to distinguish which of the AGN emission regions (sketched in Figure 1, for the size scales relevant to SIM) dominates. We use SIM's ability to measure any shift in the optical photocenter of AGN emission as a function of colour. We identify two distinct possible locations for the photocenter of the red light relative to the blue. In both cases, most of the blue light is thermal emission from the optically thick part of the accretion disk – the 'Big Blue Bump'.

> **Case 1.** Most of the red light is power-law synchrotron emission along the relativistic jet. The red photocenter will be offset along the VLBI jet direction from the blue photocenter associated with the accretion disk.
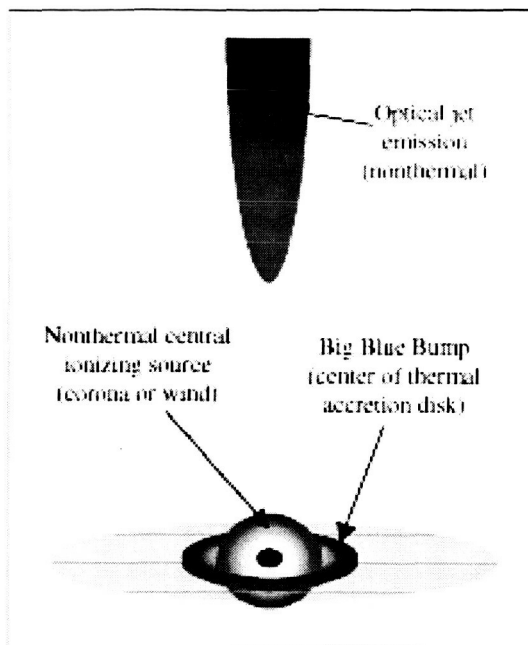
Figure 1: Schematic model of the central ionizing source (after Band & Malkan 1989) and jet (after Königl 1981) for a typical AGN. Size of the central disk/corona structure is $\sim 70 - 120\,\mathrm{R_{Sch}}$ ($\sim 100 - 160\,\mu$as for M87, or only $1 - 2\,\mu$as for a typical quasar at a redshift of 0.5). The offset between the optical jet and disk emission for 3C 345 at $z = 0.6$, based on the Königl model, is expected to be $\sim 0.4\,$pc or $80\,\mu$as.

Case 2. The red light comes from synchrotron or inverse Compton emission from a hot, magnetized corona or wind above the accretion disk. The red and blue photocenters should be coincident.

Example: Nearby radio galaxy M87. We expect the optical emission to be dominated by the accretion disk region because its jets are not pointing within a few degrees to our line of sight (Biretta *et al.* 1991). There should be no colour shift between the red and blue SIM bands, because the corona and accretion disk are axisymmetric (Figure 1). However, we expect a relatively large offset (as large as several 100 μas) between the optical photocenter and radio photocenter (which is dominated by emission from the optically thick base of the radio jet).

Binary Black Holes Do the cores of galaxies harbour binary supermassive black holes remaining from galaxy mergers? How commonly does this occur? This is a question of central importance to understanding the onset and evolution of non-thermal activity in galactic nuclei. An entire AGN black hole system may be in orbit about another similar system, as might occur near the end of a galactic merger, when the two galactic nuclei themselves merge, with a characteristic timescale is a few hundred million years. How large is the astrometric signature? Rough estimates, based on the circumstantial evidence currently available, indicate that displacements of 10 μas or more (readily detectable with SIM) may be present in a number of AGN. The best candidate is probably OJ 287 (Lehto & Valtonen 1996; Kidger 2000), with an inferred period of 24 years from variability monitoring, and a mass of 10^9 solar masses. During 5 years of SIM monitoring, the expected orbital displacement is about 15 μas.

Astrophysics of Reference Frame Tie Objects

Principal Investigator: Kenneth J. Johnston, (USNO)

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The Astrophysics of Reference Frame Tie Objects Key Science program will investigate the underlying physics of SIM grid objects. Extragalactic objects in the SIM grid will be used to tie the SIM reference frame to the quasi-inertial reference frame defined by extragalactic objects and to remove any residual frame rotation with respect to the extragalactic frame. The current realization of the extragalactic frame is the International Celestial Reference Frame (ICRF). The ICRF is defined by the radio positions of 212 extragalactic objects and is the IAU sanctioned fundamental astronomical reference frame. This key project will advance our knowledge of the physics of the objects which will make up the SIM grid, such as quasars and chromospherically active stars, and relates directly to the stability of the SIM reference frame. The following questions concerning the physics of reference frame tie objects will be investigated.
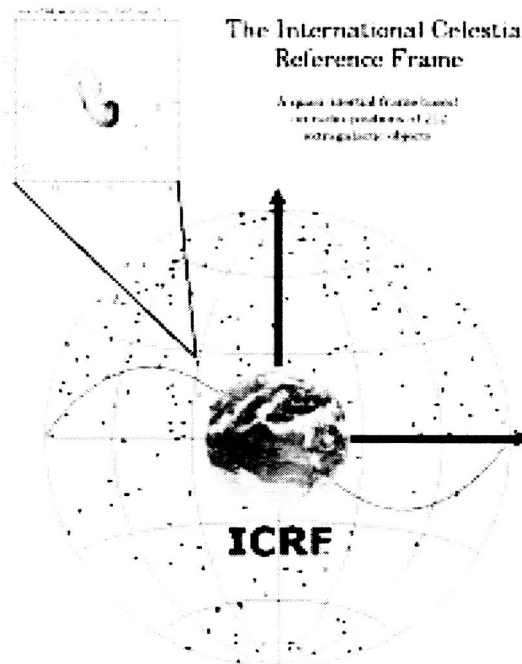
Figure 1: Figure shows a schematic representation of the ICRF as a projection of extragalactic radio sources onto the celestial sphere. The inset shows the 8.55 GHz radio frequency image of a representative source.

What is the origin of optical emission in quasars? In the standard theory of extragalactic radio sources, emission from quasars and active galactic nuclei (AGN) is assumed to be powered by a central engine (presumably a black hole) where energetic phenomena occur. The origin of the optical wavelength radiation from AGN identified with compact radio sources is not well

established. There are several possibilities: 1) the optical radiation is thermal emission from an accretion disk; 2) the optical radiation is non-thermal emission from a magnetized corona or wind emanating from the central region of the accretion disk; or 3) the optical radiation is emission from a relativistic jet beamed toward the observer. SIM observations will allow a direct test of this model.

Are the optical photo-centers of quasars compact and positionally stable on the micro-arcsecond level? It is well known that variable intrinsic structure of AGN at radio wavelengths has a significant impact on (degrades) radio positional accuracy. Currently, there is very little available information on whether the optical counterparts of the radio objects are compact at the level of astrometric precision expected from SIM. Although the core of a quasar's optical emission may originate in a region as small as 1 pc (200 microarcseconds at 1 Gpc), some degree of photocenter wander should be expected, probably correlated with optical variability. Motion of a quasar's photocenter may also result from a variable nucleus in combination with effects in the larger (albeit fainter) host galaxy.

Are binary black hole mergers responsible for quasars? Optical photocenter wander of quasars can be used to search for binary black hole signatures and thus test the hypothesis that binary black hole mergers are responsible for most quasars. A positive detection of binary black hole induced motions in the optical photocenter of quasars would be good evidence to support this hypothesis.

What is(are) the emission mechanism(s) responsible for generating radio emission in chromo-spherically active stars. Is the emission thermal, relativistic synchrotron or gyro-synchrotron? No consensus has yet developed concerning the physics of the formation and evolution of the radio emission associated with the active binary star systems. Also, for most active binaries, the location of the radio emission with respect to the binary components is unknown; e.g. is the radio emitting region centered on one of the stars, is it located in the intra–binary region, or does it surround both stars? This uncertainty can be attributed, in part, to inadequacies in the radio/optical frame link.

What causes the transition of spherically symmetric Asymptotic Giant Branch (AGB) stars to asymmetric planetary nebulae (PNe)? Models based on interacting winds have had consider-able success explaining PNe morphologies. However, it is still unknown whether the asymmetries observed in PNe are present in the progenitor AGB stars themselves, and whether these asym-metries could be produced by mechanisms such as non-radial pulsations or unseen companions. SIM observations of a number of AGB stars shown to have asymmetric envelopes, through radio observations of circumstellar masers, will allow a test of these theories.
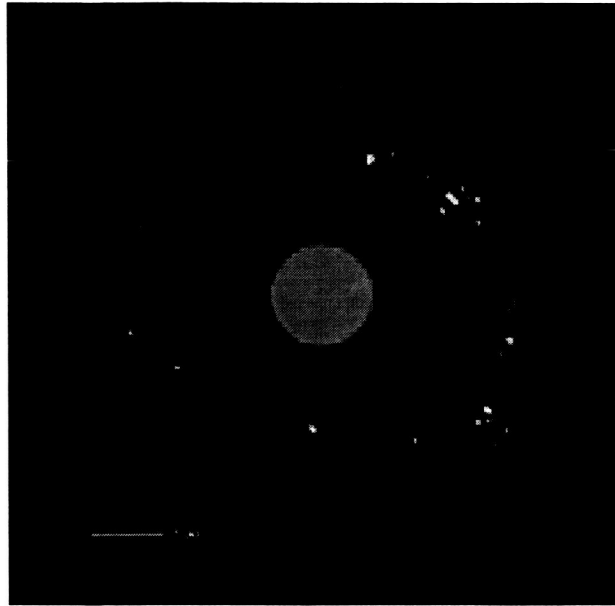
Figure 2: Figure shows the asymmetrical SiO maser shell toward the Mira variable IK Tauri with nearly a 2:1 axial ratio. The location of the stellar disk (red circle) relative to the masers is pure conjecture.

Space Interferometry Mission: Dynamical Observations of Galaxies (SIMDOG)

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Team Members:
Kirk D. Borne (Raytheon), Adi Nusser (Technion-Israel Inst of Tech), P. J. E. Peebles (Princeton), John Tonry (UH, Manoa), Brent R. Tully (UH, Manoa), Stuart Vogel (Univ of Maryland), Dennis Zaritsky (UC, Santa Cruz).

Space Interferometry Mission (SIM) will be used to obtain proper motions for a sample of 27 galaxies; the first proper motion measurements of galaxies beyond the satellite system of the Milky Way. SIM measurements lead to knowledge of the full 6-dimensional position and velocity vector of each galaxy. In conjunction with new gravitational flow models, the result will be the first total mass measurements of individual galaxies. The project includes development of powerful theoretical methods for orbital calculations. This SIM study will lead to vastly improved determinations of individual galaxy masses, halo sizes, and the fractional contribution of dark matter. Astronomers have struggled to calculate the orbits of galaxies with only position and redshift information. Traditional N-body techniques are unsuitable for an analysis backward in time from a present distribution if any components of velocity or position are not very precisely known.

Peebles made a major advance in this field when he introduced numerical action methods (NAM) to cosmology. Peebles noted that six components of phase space are accurately known: right ascensions, declinations, and redshifts of galaxies today and the initial condition of effectively zero peculiar velocities. At early times, the mass parcels that would eventually turn into galaxies simply followed the Hubble Law of expansion for that epoch. The NAM provide explicit numerical procedures that transforms cosmological N-body orbit calculations into a non-chaotic boundary value problem. SIM offers an exciting prospect – access to three more elements of phase-space for each galaxy. These extra constraints are vital since the dynamical gravitation problem naturally leads to several families of solutions for orbits and masses. SIM measurements will discriminate between orbit families, which will strongly constrain total masses and make a locally determined estimate of the global mass density of the Universe. We will have sufficient information to measure dark matter mass to the outermost edges of galaxies, and to discern the sizes of extended halos. These halos may extend far beyond the stars and gas of the observable galaxies. Accurate distances are needed to complement proper motions and will be obtained through a parallel program of observations.

Through other Key Projects, SIM will determine precise distances to Cepheid variable stars and the red giant and horizontal branch stars that serve as standard candles. Bootstrapping on these calibrations, and in the course of a program of support observations for SIM, our team will derive distances at the level of 7 percent for all our target galaxies from two methods: from the luminosity of the tip of the red giant branch of old metal-poor stars and from the Balmer line equivalent widths of A,B supergiants, the very stars used for the SIM proper motion studies. With this anticipated level of accuracy, we will locate galaxies to better than 300 kpc across the ~ 4 Mpc region of interest. This galaxy localization undertainty is comparable to the anticipated dimensions of halos. One can expect to resolve the mass of groups into the masses of individual galaxies. We are planning an observing campaign prior to the launch of SIM in order to select target stars. Color magnitude information about many of the brightest candidate stars have already been published, although usually only parts of the host galaxies have been surveyed. In a small minority of cases here are spectroscopic studies that confirm that the candidates from

photometric studies are evolved supergiants in the host galaxies, the kinds of stars needed for SIM observations. Hence, the practicality of this SIM Key Project is established, but there will have to be spectroscopic and photometric monitoring of several hundred stars before we can make the final selection of program targets. A range of analytical techniques will be applied to the set of SIM proper motions, inlcuding N-body simulation statistics, the cosmic virial theorem, Zel'dovich approximations, and numerical action methods. Over the next decade, we will advance these techniques and adapt them to the special case of our Local Group and neighboring groups. Within the vicinity of the Local Group, gravity perturbations are large so orbits have evolved into the non-linear domain. Most dynamical studies in cosmology avoid this regime. Our team initiated, and has been closely involved in the development of NAM, the Numerical Action Method, the only mathematical tool that solves for orbits in the fully non-linear regime. The investigators are experienced in data handling, format issues, and data reduction.

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

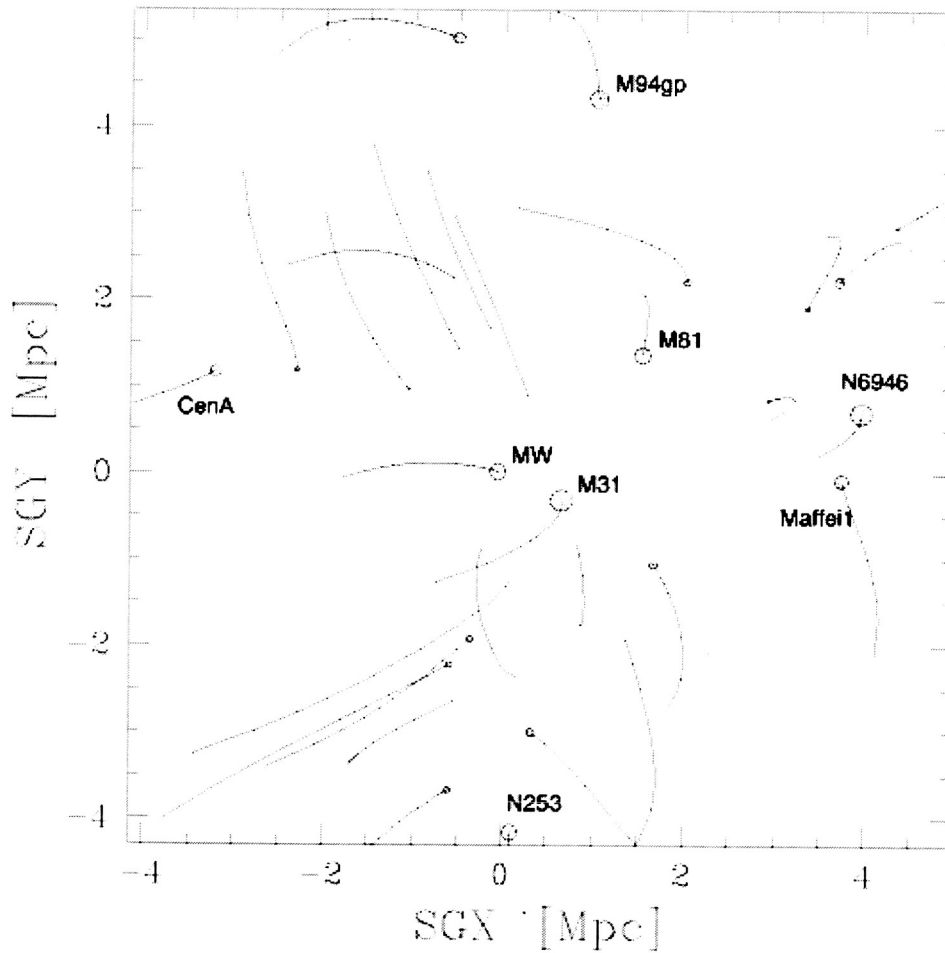Figure 1: The trajectories of galaxies within 5 Mpc of the Milky way. The 52 orbits are from solutions with 12 masses adjusted to best fit the present distances. Present positions are circles. The sizes of the circles are proportional to masses. Distance measurements for 37 galaxies were available and guided the mass solutions. Note that the crossing times are comparable to the age of the universe so the orbits are relatively simple.

Synthesis Imaging at Optical Wavelength with SIM

Principal Investigator: Ronald J. Allen (STScI)

Team Members:
Torsten Boeker (STScI), Roeland P. van der Marel (STScI)

Synthesis Imaging with SIM

The Space Interferometry Mission (SIM) will be the first space astrophysics instrument to provide a capability for synthesis imaging at optical wavelengths, offering the promise of imaging high-surface-brightness targets with more than 4 times the best resolution attainable with the Advanced Camera on the Hubble Space Telescope. The present SIM design includes astrometric science interferometers at 8 and at 10 meters, and a guide interferometer at 5.5 meters which can also be used for science targets. By using data from all 3 baselines and combining observations taken at many small increments in roll angle, SIM can image a field of view of $\sim 1''$ with a resolution of FWHM $\approx 0.008''$ at $\lambda 500$ nm. The point spread function (PSF) of the images produced directly from this data show many low-level spurious responses spread over the entire image. However, the truly incredible phase stability of SIM's interferometers means that these responses can all be calculated to a very high degree of accuracy, opening the way for the application of image restoration algorithms such as those popular in radio astronomy. Which restoration methods are best for SIM data, and how to incorporate additional constraints (such as HST imaging of the same fields), are topics of ongoing studies at the Space Telescope Science Institute in Baltimore.

Imaging Science with SIM

SIM imaging will be especially useful on crowded fields containing many high-brightness targets. Such fields include the central regions of galaxies out to the Virgo cluster (including active nucleii and jets), and the swarms of stars in the cores of Galactic globular clusters. There are indications that the central regions of some globular clusters may contain black holes, similar to the situation currently thought to occur in the centers of many galaxies. These massive objects dramatically affect the motions of nearby stars. Images made with SIM at several epochs spread over the lifetime of the mission will yield positions, proper motions, and perhaps even accelerations of cluster stars, providing unique new information on the masses of central black holes. If SIM were to fly tomorrow, we would plan on observing the nucleus of the nearby spiral M 31 and the central core of the Galactic globular cluster M 15 (see Figure 1); however, the specific targets to be observed first will be chosen a year or two before launch, depending on the latest developments at that time.

As an indication of the capability of SIM to image complex fields, Figure 2 shows a simulation for the nuclear star cluster in the core of M 31. The positions of stars as faint as V = 21 mag can be determined in this simulation to a precision of better than $0.0005''$. The motion of a typical star in this field will produce a position shift of $\sim 0.0008''$ after 5 years.
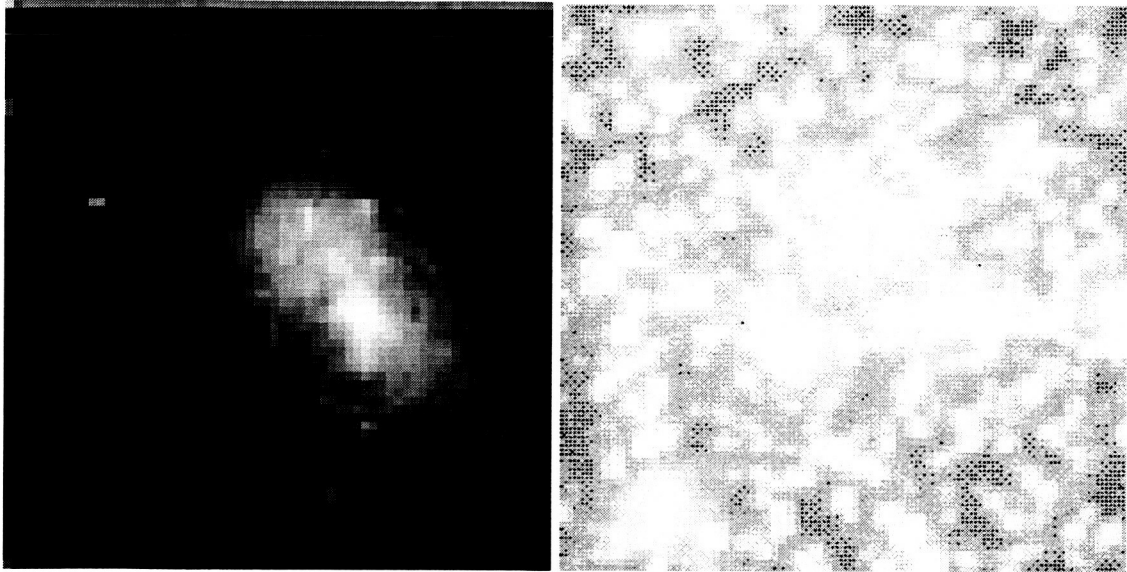
Figure 1: HST images of our two highest priority targets. a) The central 3.5″ of M 31 in a greyscale representation that emphasizes B-band and UV light. The circle denotes a 1.2″ diameter aperture, close to the expected SIM field of view. The SIM imaging-mode resolution will be $\approx 0.7\%$ of the size of the circle. b) The nuclear region of the globular cluster M 15 at the same scale as the left panel. The adopted stretch only slows the brighter stars ($V \sim< 17$); the proposed SIM data will yield proper motions for stars as faint as $V = 21$–22.

Figure 2: a) input source model for the nuclear star cluster in M 31. The stars in this simulation range from 21 to 23 mag in V. b) reconstructed image after 1200 CLEAN iterations. The simulation is for a total on-source integration time of 4 h and a "full" set of SIM baselines.

Exceptional Stars Origins, Companions, Masses and Planets

Principal Investigator: Shrinivas R. Kulkarni (Caltech)

Team Members:
Bradley M. S. Hansen (Caltech), Sterl Phinney (Caltech), Martin H. van Kerkwijk (Utrech Univ), Gautam Vasisht (JPL).

As SIM Interdisciplinary Scientist, we will study the formation, nature and planetary companions of the exotic endpoints of stellar evolution. As part of this program, we will contribute to the mission:

- A tie of the SIM frame to the ecliptic (Solar System ephemeris) frame with better than 20 microarcsec precision.

- A study of the problem of amplitude calibration for SIM, and the requirements for precision work on binary stars unresolved by the individual SIM apertures.

- A study of the effects of distant companions to grid stars, in particular on SIMs sensitivity to long-period binaries, and suggestions for avoiding these effects.

Our science begins with stars evolving from asymptotic branch giants into white dwarfs. We will determine the parallax and orbital inclination of several iron-deficient post-AGB stars, who peculiar abundances and infrared excesses are evidence that they are accreting gas depleted of dust from a circumbinary disk. Measurement of the orbital inclination, companion mass and parallax will provide critical constraints. One of these stars is a prime candidate for trying nulling observations, which should reveal light reflected from both the circumbinary and Roche disks. The circumbinary disks seem favorable sites for planet formation.

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

Moving up in mass, we will measure the orbital reflex of OB/Be companions to pulsars, determine natal kicks and presupernova orbits, and expand the sample of well-determined neutron star masses. We will obtain the parallax of a transient X-ray binary, whose quiescent emission may be thermal emission from the neutron star, aiming for precise measurement of the neutron star radius.

Neutron stars receive large kicks at birth. OB companions unbound by this kick become runaway OB starts. Yet some OB stars appear so high above the galactic plane they could not have gotten there in their lifetime. Some may be misidentified post-AGB stars, some may have formed 10kpc above the Galactic plane; we will find their true nature from their proper motion and parallax (or limit thereto).

A few neutron stars whose kicks are suitably oriented can remain in low-mass X-ray binaries. Proper motion and parallax measurements, combined with radial velocity, fix their true space velocities, and thus test the scenarios for their formation.

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

Masses and Luminosities of X-Ray Binaries

Principal Investigator: Andreas Quirrenbach (UC San Diego)

Team Members:
Sabine Frink (UC San Diego), John Tomsick (UC San Diego)

Summary

Using SIM, we will perform narrow-angle observations of several X-ray binaries to determine their orbits, and we will observe about 50 X-ray binary systems in wide-angle mode to measure their distances and proper motions. Sources with mass estimates for the compact component of greater than $3\,M_\odot$ are generally called "black hole candidates" since this mass is above the theoretical neutron star limit. Narrow-angle observations of these sources provide a direct test of the dynamical mass estimates on which the black hole evidence is based. Better measurements of the black hole masses will provide constraints on possible evolutionary paths that lead to black hole formation. When combined with X-ray data, mass measurements may provide additional constraints on the black hole spin. Precise mass determinations of neutron star systems can address the question of whether neutron stars can be significantly more massive than $1.4\,M_\odot$, which would eliminate soft models of the neutron star equations of state. The wide-angle observations will probe the Galactic distribution of X-ray binaries through parallaxes and proper motions. They will also eliminate the uncertainties in the luminosities of individual sources, which is currently up to a full order of magnitude. This will enable more detailed comparisons of X-ray observations to physical models such as advection-dominated accretion flows (ADAFs). We intend to carry out the following measurements:

- Determine the orbits of two black hole candidates to measure the black hole masses.

- Obtain precise mass measurements for two neutron star systems to constrain neutron star equations of state.

- Determine the distances and thus luminosities of selected representatives of various classes of X-ray binaries (black hole candidates, neutron stars, jet sources).

- In the process of distance determination, proper motions will also be measured, from which the age of the population can be estimated.

Mass Measurements: Current Status and Methods

The following equation shows the parameters that must be determined to measure the compact object mass (M_X) for X-ray binaries using the current methods

$$M_X = \left(\frac{1+q}{q}\right)^2 \frac{f_{\mathrm{opt}}}{\sin^3 i} \quad , \tag{3}$$

where $f_{\mathrm{opt}} = PK_{\mathrm{opt}}^3/2\pi G$, P is the orbital period, i is the binary inclination, q is the mass ratio of the binary components ($q = M_X/M_{\mathrm{opt}}$) and K_{opt} is the semi-amplitude of the radial velocity curve for the optical companion. For black hole and non-pulsating neutron star X-ray binaries,

measurements of i and q depend on modeling of the system, introducing significant uncertainty. A direct measurement of q is possible for pulsating neutron star systems, but modeling is still necessary to determine i. Figure 1 shows the neutron star and black hole masses that have been measured.
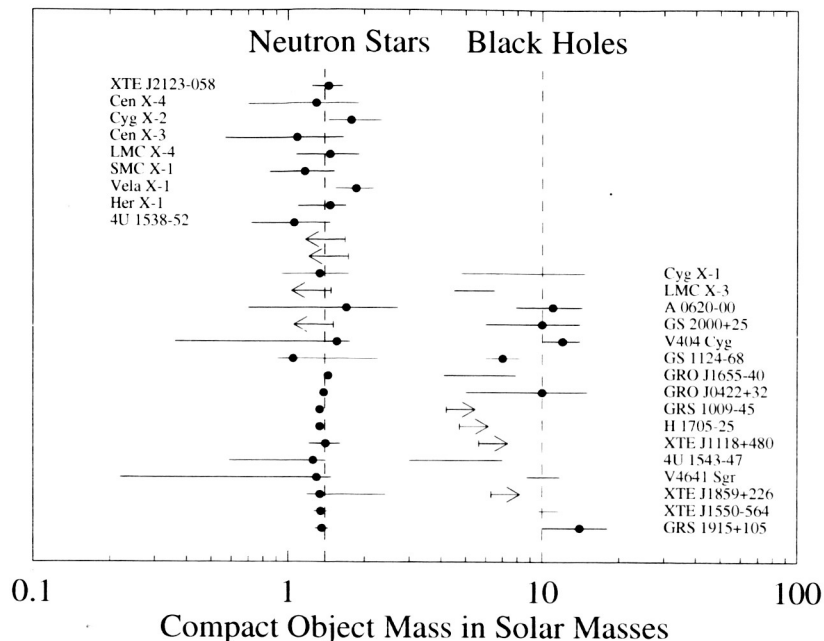

Figure 1: Compact object mass measurements as of 2001 November. There is an apparent gap between the neutron star masses, which cluster near $1.4\,\mathrm{M_\odot}$, and the higher black hole masses. The neutron star X-ray binary systems are labeled, and the unlabeled systems are binary radio pulsars.

Narrow-Angle SIM Observations

The main goal of the narrow-angle SIM observations is to measure compact object masses in black hole and neutron star X-ray binaries. The size of the astrometric signature depends on the binary orbital period, the masses of the binary components and the distance to the source. Figure 2 shows simulated SIM observations for two black hole systems (Cyg X-1 and GRO J1655–40) with significantly different binary inclinations (i).

Wide-Angle SIM Observations

For the wide-angle SIM observations, the goals are to measure the distances and proper motions for about 50 X-ray binaries. Currently, distances to most X-ray binaries are very uncertain, leading to large uncertainties in the luminosities of these sources. Here, we list some of the source types we plan to observe, and discuss motivations for the SIM observations.
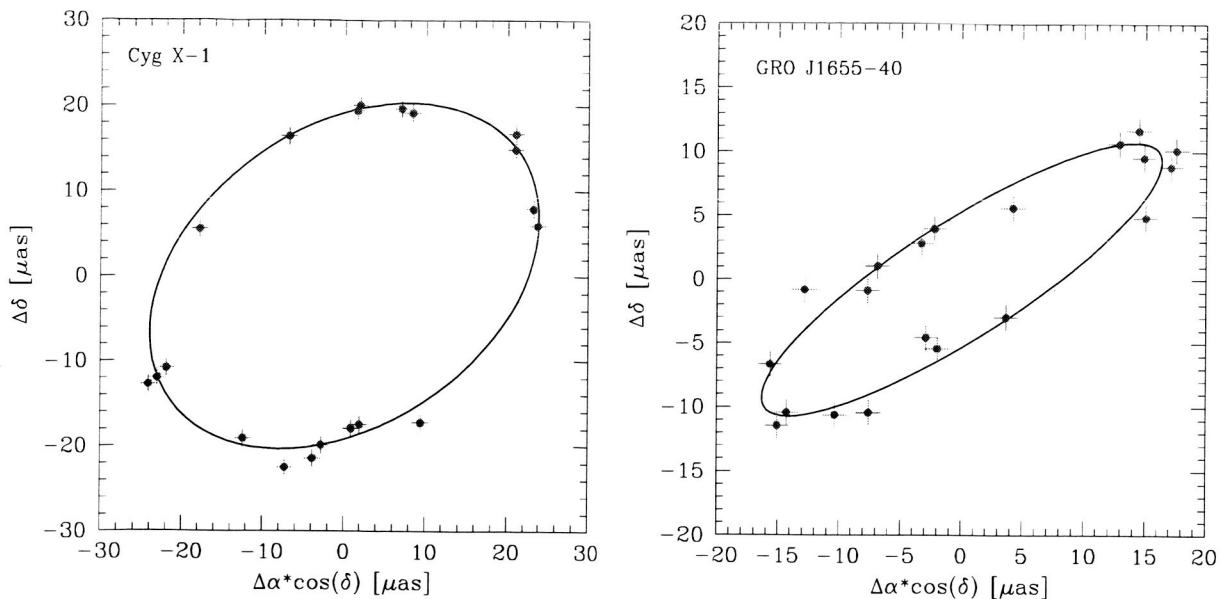
Figure 2: *Left panel*: Simulation of *SIM* observations of Cyg X-1, showing that *SIM* will be able to detect the binary motion of the system. A binary inclination of 47° was assumed. *Right panel*: Simulation of *SIM* observations of GRO J1655–40, assuming a binary inclination of 70°.

- A class of neutron star X-ray binaries called "Z-sources" (e.g., Sco X-1, Cyg X-2, GX 17+2) are thought to emit at close to the Eddington luminosity. Distances are necessary to determine if this is the case.

- Low magnetic field neutron stars produce X-ray bursts (e.g., EXO 0748-676, 4U 1254–690). It is important to know the X-ray burst luminosities for theoretical models of this phenomenon.

- Observations of X-ray transients in quiescence (e.g., GRO J1655–40, Cen X-4, Aql X-1) suggest that black hole systems are less luminous than neutron star systems for a given mass accretion rate. According to the ADAF model, this may demonstrate the presence of black hole event horizons.

- Accurate distances to radio jet sources (e.g., GRO J1655–40, XTE J0421+560, SS 433, V4641 Sgr) are important for determining the jet velocities.

- Some sources at high Galactic latitude appear to be unusually far from the Galactic plane (e.g., Her X-1).

- Proper motion measurements will allow us to estimate the age of the X-ray binary population.

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

Principal Investigator: Stuart Shaklan (JPL)

Team Member: Xiaopei Pan (JPL)

The Space Interferometry Mission (SIM) is capable of detecting and measuring the mass of terrestrial planets around stars other than our own. It can measure the mass of black holes and the visual orbits of radio and x-ray binary sources. SIM makes possible a new level of understanding of complex astrophysical processes while bestowing a new perspective on our place in the Universe.

SIM achieves its high precision in the so-called "narrow-angle" regime. This is defined by a 1° diameter field in which the position of a target star is measured with respect to a set of reference stars. The observation is performed in two parts: first, SIM observes a grid of stars that spans the full sky. After a few years, repeated observations of the grid allow one to determine the orientation of the interferometer baseline. Second, throughout the mission, SIM periodically observes in the narrow-angle mode. Every narrow-angle observation is linked to the grid to determine the precise attitude and length of the baseline.

The narrow angle process demands patience. It is not until five years after launch that SIM achieves its ultimate accuracy of 1 microarcsecond (μas). The accuracy is degraded by a factor of ~ 2 at mid-mission.

Our work proposes a technique for narrow angle astrometry that does not rely on the measurement of grid stars. This technique, called Gridless Narrow Angle Astrometry (GNAA) can obtain μas accuracy and can detect extra-solar planets and other exciting objects with a few days of observation. It can be applied as early as during the first six months of in-orbit calibration (IOC).

The motivations for doing this are strong. First, and obviously, it is an insurance policy against a catastrophic mid-mission failure. Second, at the start of the mission, with several space-based interferometers in the planning or implementation phase, NASA will be eager to capture the public's imagination with interferometric science. Third, early results and a technique that can duplicate those results throughout the mission will give the analysts important experience in the proper use and calibration of SIM.

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

As with narrow angle astrometry at a telescope, the conformal transformation absorbs SIM instrumental parameters. To first order, baseline length errors cause angular scale errors, baseline orientation errors cause rotational errors about the center of the reference frame, and the metrology constant term is a translation along the direction of the baseline. The conformal

transformation solves the scale, rotation, and translation of the observed reference frame without requiring the intermediate step of exact baseline determination. The absolute scale is lost, but it is estimated with a precision approximately given by the a priori scale knowledge of the field size.

Simulation results shows that GNAA can measure changes in the position of the target relative to the reference frame at the micro-arcsecond level. Even for extended periods in which the reference frame deforms by 10 mas, the noise level remains $\sim$ 1 micro-arcsecond.
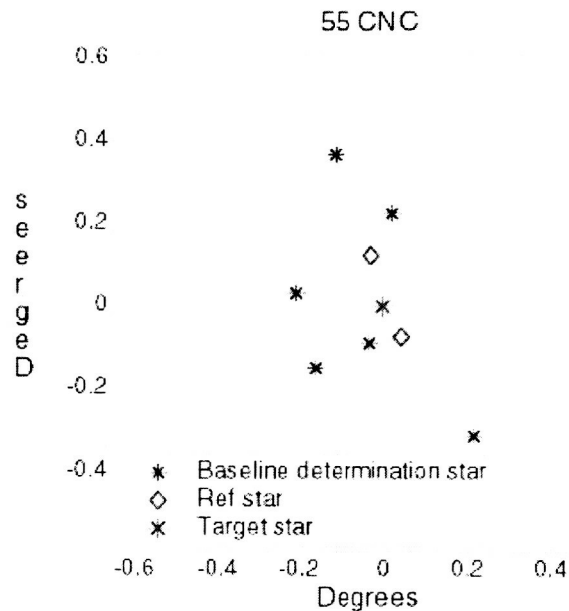

Figure 1: Figure shows the reference frame around a typical target, 55 Cnc. All stars shown in the 1° field have visual magnitude brighter than V=10.5. The figure indicates stars that are used to determine instrument parameters (blue symbols), stars that serve as independent reference stars (diamonds), and the target 55 Cnc (red symbol). 55 Cnc has a 14.7 day period, Msini = 0.84 Jupiter masses, and a semi-major axis of 8 micro-arcseconds corresponding to 0.11 AU.

We intend to use the GNAA technique to observe short-term periodic signals, including known and potential extra-solar planets, the black-hole Cyg X-1 (P = 5.6 d), as well as Radio and X-ray binary systems, e.g. the Be star LSI 61303 (P = 26.5 d), and similarly V725 Tau, X Per, V801 Cen, HD 63666, HD 91188, all with periods < 35 d.
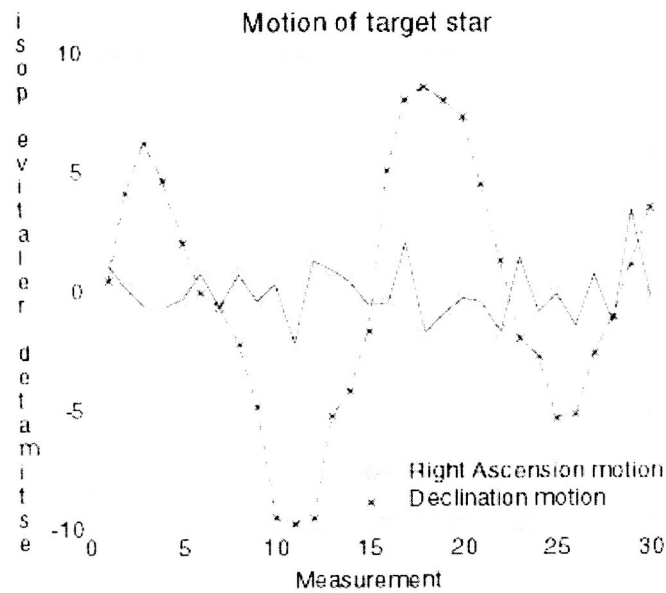
Figure 2: Estimated relative positions from 30 daily observations of 55 Cnc. Each day, the baseline is oriented to 3 positions rotated 120° about the line of sight to the target. For demonstration purposes, the 8 uas signal is assumed to be a pure N-S sine wave. The R.A. axis thus indicates the noise level. The simulation assumes 50 picometers delay measurement errors per star, and reasonable assumptions with respect to baseline positioning control and knowledge. The astrometric precision is 1.0 μas on each axis for each 3-baseline (3-hour long) observation.

Open and Globular Cluster Distances for Extragalactic, Galactic, and Stellar Astrophysics

Principal Investigator: Guy S. Worthey (Washington State Univ.)

One of the hallmarks of SIM's few-milliarcsecond astrometric precision is its ability to obtain accurate parallax measurements across more than half of the Galaxy. On the Milky Way analog below, the best space-based parallaxes to date lie within the yellow dot marked "Sun".
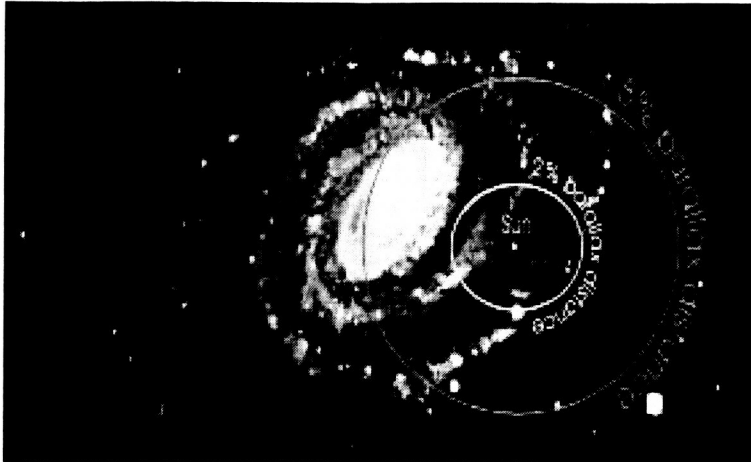

Figure 1: SIM's astrometric precision will allow parallax distances to be measured with 5% accuracy well past the Galactic center, and distances of stars within ~ 3 Kpc to measured with less than 2% uncertainty. This 3 Kpc shell contains the "near half" of the traditional extragalactic distance ladder: RR Lyrae variables and Cepheid variables that range over all [Fe/H], plus many star clusters used for main-sequence fitting.

The "open and globular" project obtains parallax distances to a set of star clusters. One important goal is to pinpoint the zeropoint of the distance scale for main-sequence fitting. Another goal is to improve stellar evolutionary isochrones and integrated light models. Another goal is to use the clusters themselves to address unsolved problems of late-stage stellar evolution and Galactic and extragalactic chemical evolution. The clusters to be observed are chosen to span the widest possible range of abundance and age, to be as rich as possible, and to be as well-studied as possible.

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

- This project will provide a definitive collection of star cluster color-magnitude diagrams for calibration of stellar evolutionary isochrones. With true distance measured with SIM and abundances from high-resolution spectroscopy, there will be virtually no "wiggle room"

for isochrone fits: any isochrones that are computed must pass through each cluster's color-magnitude diagram with least-square errors less than the post-SIM observational errors. There is an accompanying program of photometry and spectroscopy to insure that isochrones of almost any age and metallicity will have observational analogs available for comparison. I refer to this collection of parameter-spanning clusters as the "cluster network."
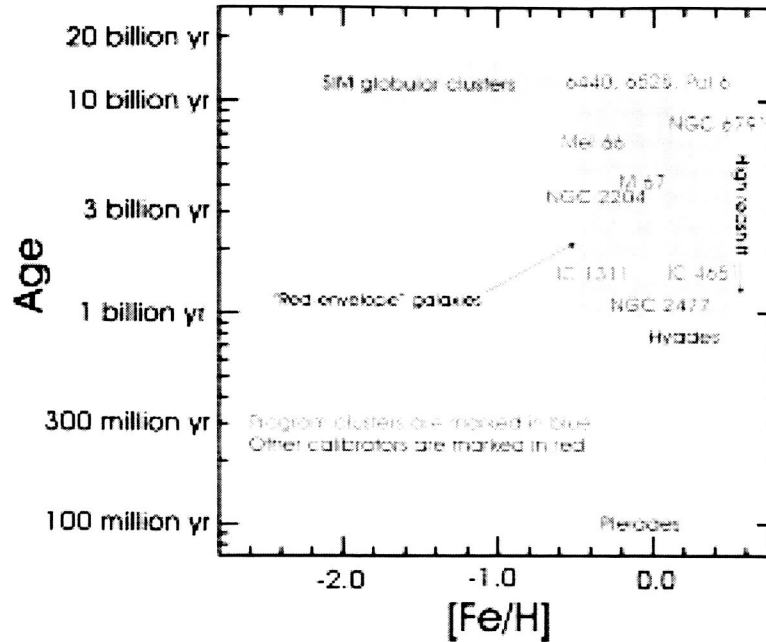

Figure 2: An age-metallicity diagram in which the targeted Galactic star clusters appear. The ellipse marked "SIM globular clusters" refers to the Chaboyer Key Project that targets the old, metal-poor cluster population. These clusters are also part of the "network," as are the nearby Hyades and Pleiades whose distances were pinpointed by Hipparchos. The ten clusters targeted by this proposal are marked in blue with ages between 1 and 12 billion years and [Fe/H] between -0.5 and +0.5. A box marked "red-envelope galaxies" refers to the appropriate age and metallicity range for non-star forming (red) galaxies at redshifts less than about 2. Longer lookback times at higher redshift mean that one is looking at younger galaxies.

- The "cluster network" calibration will yield better isochrones and better integrated-light models for use in studies of extragalactic stellar populations. The benchmark targets we have adopted are non-star forming galaxies at high redshift for which good spectra will be available by 2015. Our goal is to derive 5% mean ages for these galaxies, thus uncovering their formation history. The figure above illustrates the ages and abundances of the selected clusters in comparison to the parameter space of the target red envelope galaxies.

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