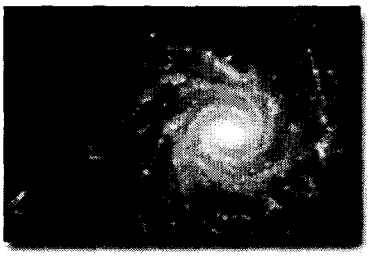
SIM Spotlight: EXTRAGALACTIC ASTROPHYSICS



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EXTRAGALACTIC ASTROPHYSICS

SIM will obtain proper motions for a sample of 27 galaxies, the first proper motion measurements of galaxies beyond the satellite system of the Milky Way. These measurements lead to knowledge of the full six-dimensional position and velocity vector of each galaxy. In conjunction with new gravitational flow models, the result will be the first total mass measurements of individual galaxies. SIM measurements will strongly constrain galaxy total masses and make a locally determined estimate of the global mass density of the Universe. There will be sufficient information to measure dark matter mass to the outermost edges of galaxies, and to discern the sizes of extended halos that may extend far beyond the stars and gas of the observable galaxies.

Observations of extragalactic objects with SIM will allow the study of parsec-scale structures in the optical waveband for the first time. Are the optical photo-centers of quasars compact and positionally stable on the microarcsecond level? There are many theoretical reasons to expect that the most variable quasars and AGN will show motion at several 10s of microarcseconds. Changes in their optical positions will be resolvable by SIM at the few μas level. In the standard theory of extragalactic radio sources, emission from quasars and AGN is assumed to be powered by a central engine (presumably a black hole). 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 determine which source dominates by looking at positional shifts across the optical waveband.

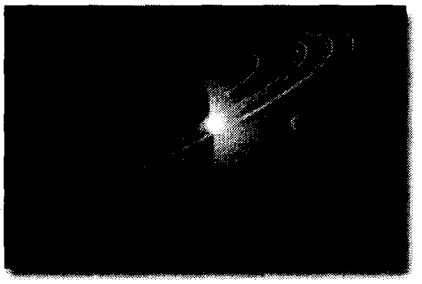
Since the parallax of a quasar is immeasurably small, SIM does not need to determine it. A quasi-inertial reference frame, formed by stars within a few degrees of the main target, will be adequate. Because AGN variability occurs on a variety of timescales, SIM will be able to deliver meaningful results relatively early in the mission. As the mission progresses, the results can be refined by tying those reference stars to the astrometric grid. For quasar studies SIM will allow doubly differential astrometry by searching for color-

dependent position shifts (across the optical waveband) and their vector time-dependence on the sky. This experiment is differential in both position and wavelength.

SIM will also search for direct evidence of binary black hole systems buried within a host galaxy. In these systems, one or both of the massive black holes may have an active galactic nucleus (AGN) surrounding it. The two holes, along with their AGN, orbit their common center of mass. Significant proper motions, detectable by SIM, occur only for relatively close binaries. This might occur near the end of a galactic merger event, when the two galactic nuclei themselves merge, with a characteristic timescale of a few hundred million years. 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 OJ287, with an inferred period of 24 years from variability monitoring and a mass of 109 solar masses. During 5 years of SIM monitoring, the expected orbital displacement is about 15 μas.

Visit http://planetquest.jpl.nasa.gov/SIM/sim_index.html and http://planetquest.jpl.nasa.gov/Navigator/sim_nav.html for more information.

SIM Spotlight: GALACTIC ASTRONOMY



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GALACTIC ASTRONOMY

SIM will 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.

By selecting suitable "test particles" -- such as subsets of the SIM astrometric grid stars and samples of the major components (bulge, disk, halo, satellite system) of the Galaxy -- SIM will perform a definitive characterization of the mass distribution within the Milky Way.
SIM will:

- Determine R_o (the Sun-Galactic Center distance) by measuring the parallax of the Galactic Center.
- Measure the rotation speed of the Sun around the Galaxy.
- Establish the rotation curve of the Milky Way, which is unknown outside the solar circle (and therefore makes the Milky Way a poorly understood galaxy from a Tully-Fisher sense).
- Measure the proper motions for orbits of every Milky Way globular cluster and dwarf satellite galaxies and a large number of open clusters.
- Measure the mass and mass distribution of the Milky Way.

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 the Milky Way's halo is due to the uncertainty in the distance scale to Population II objects. SIM will obtain accurate parallaxes to a number of Population II objects (globular clusters and field stars in the halo) resulting in a significant improvement in the Population II distance scale and greatly reducing the uncertainty in the estimated ages of the oldest stars in our galaxy.

These SIM observations and resultant age determination for the universe will provide an important, independent check of the preferred cosmological model.

Besides measuring the proper motions of every globular cluster and numerous open clusters, SIM will observe about two dozen globular and open star clusters in order to obtain accurate determinations of their chemical abundances, ages, and the amount of foreground interstellar reddening. The needed measurements are precision parallaxes and proper motions. Results from these clusters illuminate the behavior of different evolutionary stages with star age and metal abundance when applied to rare stars in the tip of the red giant branch, horizontal branch, and asymptotic giant branch. In addition, the results derived from these measurements permit calibration of stellar evolutionary isochrones, applicable to other clusters and models of integrated light.

In turn, these calibrations can be used for much better estimates of the age and metal abundances of high-redshift galaxies, and thus a better understanding of galaxy formation. These measurements can also be used to improve the cosmic distance scale.

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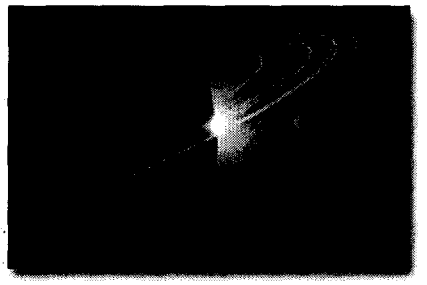
SIM Spotlight: PLANET DETECTION



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PLANET DETECTION

The SIM planet search program consists of three main scientific areas:

- **Deep search.** SIM will search for terrestrial planets around the nearest ~250 stars. This "Deep Search" program is the most demanding in terms of astrometric accuracy. "Deep Search" will use the full capability of SIM to make relative positional measurements accurate to 1 μas.
- **Broad survey.** A second planet search program called the "Broad Survey" is aimed at a much larger ~2000 star sample, albeit at lower positional accuracy (~3 μas). The goal of this program is to explore the prevalence of Neptune and larger mass planets in all stellar types in our part of the Galaxy.
- **Planets around young stars.** The third component of the SIM planet search program is the search for Jupiter mass planets around young stars. To date, more than 100 planets have been discovered outside our solar system. The vast majority of these planetary systems are very different from our own. In particular, the discovery of 'Hot Jupiters' has led to a variety of theories on how such planets are formed. The search for planets around young stars is aimed at studying planetary systems with one or more Jupiter mass planets before the system has reached long term equilibrium.

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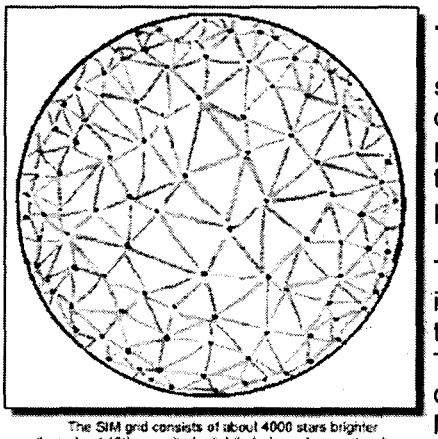
SIM Spotlight: REFERENCE FRAMES



The SIM grid consists of about 4000 stars brighter than about 13th magnitude distributed evenly over the sky.

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REFERENCE FRAMES

SIM will yield 4 microarcsecond (μas) absolute position measurements. In order to accomplish this, SIM will define a new astrometric reference frame, using a grid of approximately 1300 stars with positions accurate to 4 μas. Unlike most survey instruments, SIM will maintain this astrometric accuracy down to the faintest magnitudes. This ability opens up the opportunity for astrometry of active galactic nuclei to better than 10 μas at magnitudes in the range V =16 to 18.

A significant side benefit of the SIM grid program is establishing a precision frame tie between optical and radio frames via SIM astrometric observations of optical (radio-loud) quasars. The current quasar-based reference frame is the International Celestial Reference Frame, which is tied to optical observations through Hipparcos observations of radio-bright stars. Chromospherically active stars are very interesting scientifically, but they make poor reference objects because of their extended sub-structure (see the Stellar Astrophysics handout). By using quasars, the SIM frame tie will eliminate the need to rely on stars.

ASTROMETRIC GRID

SIM will build its own precision reference frame because no other mission has ever before measured star positions with such accuracy. This is accomplished by creating a network of relative positions over the entire sky. By tying together sets of relative measurements of star separations, we can create a rigid reference frame. The system is much like laying out a lattice of stiff yardsticks into a frame.

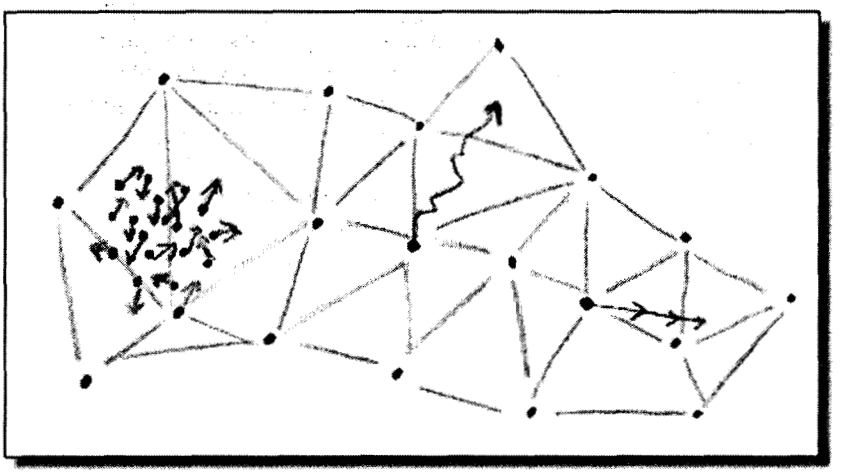
The astrometric grid is a model of the positions and motions of a particular collection of astronomical objects. These objects will mostly be stars, but some will be quasi-stellar objects (or quasars) that provide an extragalactic anchor for the astrometric grid. Grid objects will be chosen to uniformly cover the entire sky.

SIM will observe the grid objects continuously throughout a five year mission. The collected data will be used to calibrate the instrument and the positions and motions of the objects in the grid will be computed. This calibration is performed by fitting the grid model to the set of grid observations that SIM has collected. The calibration can then be used to perform astrometric data reductions of science targets observed with SIM.

The grid moves

At SIM's level of accuracy, there are no "fixed" stars. All stars will move in a well-resolved fashion in parallactic ellipses, due to the motion of Earth around the Sun, superimposed on the true movement of the stars through space, their proper motion.

Some observations only require relative observations, for which a local grid will be sufficient. For example, the detection of planetary companions does not require the full knowledge of absolute positions but can rely on changes in position relative to reference stars close to the object of interest.



Science with the grid

Once sufficient grid observations have been made to build up a reliable grid model, observations of grid objects made in conjunction with observations of science objects allow SIM to perform accurate astrometry on science targets. SIM observes grid objects and uses the grid model to solve for interferometer parameters (baseline length and orientation). This process provides the proper calibration for observations of science objects. Depending on the nature of a science target, the regular astrometric model parameters can be determined in this mode. More complicated models, such as reflex orbital motion or microlensing shifts, may also be used.

It is important to note that it is not necessary for the grid solution to be completed before science operations begin – instead, combined grid and science measurement scenarios are made, and then interpreted in the context of the grid solution current at that time. As the grid solution matures, science measurements are updated using the improved grid solutions.

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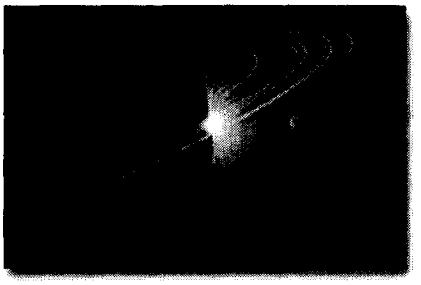
SIM Spotlight: Stellar Astrophysics



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STELLAR ASTROPHYSICS

SIM will investigate the mass distribution and mass content of the Galaxy --- from massive stars to barely glimmering brown dwarfs, and from hot white dwarfs to exotic black holes. It 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 all stellar populations. Samples will include distant clusters that span a factor of 5000 in age, and commonplace stars and substellar objects 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. Mass information is required to calibrate the evolutionary tracks of pre-main sequence stars that serve as a chronometer ordering the events that occur during the evolution of young stars and planetary systems. Accurate masses are also needed for stars that have extrasolar planets.

To put our knowledge of stellar evolution on a firmer footing, SIM will measure the distances and orbital properties of ~ 200 stars precisely enough to determine the masses of single and binary stars to an accuracy of 1%. This, in turn, will constrain stellar astrophysics models more tightly than ever before. SIM will (1) define the mass-luminosity relation for main sequence stars in five fundamental clusters and associations 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.

Wide angle measurements will determine parallaxes for the study of post-Asymptotic Giant Branch (post-AGB) stars. Narrow angle measurements will be made to determine the orbital inclinations of several iron-deficient post-AGB stars (in binary systems), whose peculiar abundances and infrared excesses are evidence that they are accreting gas from a circumbinary disk depleted of dust. Measurement of the orbital inclination, companion mass, and parallax will provide critical constraints models.

SIM will help our understanding of the transition of spherically symmetric Asymptotic Giant Branch stars to asymmetric planetary nebulae (PNe). Models based on interacting winds have had considerable 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 asymmetries 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.

SIM can probe the Galactic distribution of X-ray binaries by measuring the parallaxes and proper motions of about 50 X-ray binaries. These measurements 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.

Precise observations of several X-ray binaries will be made to determine their orbits. The main goal of these narrow-angle SIM observations is to measure compact object masses in black hole and neutron star X-ray binaries. These objects are faint and will make use of SIM's ability to make accurate observations of faint objects.

A census of the stellar population of the Galaxy will be made by SIM including both ordinary stars and "dark" stars. Main sequence and giant 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 dark 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 only a stellar-size mass, the lensing effect can be detected in two ways: photometrically, by measuring the magnification of the source by the lens, and astrometrically, by measuring the shift in the centroid of the two images. 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.

SIM will be in a trailing solar orbit, moving away from the Earth at 0.1 AU/yr. From the difference in the perspective of the event as seen by SIM and groundbased telescopes, one can reconstruct more details of the microlensing event. Thus SIM photometry (a byproduct of its astrometric observations) can be used to determine the geometric parameter needed to compute the lens' mass.

An alternative mass determination relies on proper motion measurements. The proper motion of nearby stars will cause them to pass in front of a more distant star, close enough to allow a measurable deflection of the distant star's light. By measuring this deflection with SIM, the mass of the nearby star can be measured to 1% accuracy.

SIM will probe the physics of chromospherically active stars. In close 'active' binary systems there are interactions between the stars that are known to generate radio emission. The emission mechanism(s) responsible for generating radio emission in chromospherically active stars is not yet understood. Is it thermal, relativistic synchrotron, or gyro-synchrotron? 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. This limitation will be eliminated by the SIM frame tie (see the Spotlight on *Reference Frames*).

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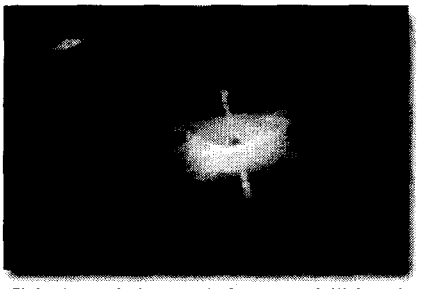
SIM Spotlight: ROTATIONAL SYNTHESIS IMAGING



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ROTATIONAL SYNTHESIS IMAGING

SIM will be the first phase-stable optical interferometer ever built. Fringes will be stable to better than 1/100 of a wavelength over time scales of many minutes, a capability which is not likely to be achieved any time soon with ground-based instruments owing to the perturbing effects of Earth's atmosphere. SIM will provide complex fringe visibility data (fringe amplitude and phase) of a quality to rival the best ground-based radio interferometers such as the Very Large Array, and do so at wavelengths that are a factor of >14,000 smaller. This feature of SIM is, of course, the reason for SIM's tremendous astrometric accuracy, but in principle it also permits use of SIM data to image astronomical objects using the techniques of synthesis imaging that are well known from radio astronomy.

SIM will image high surface brightness, low-complexity targets with more than four times the best resolution attainable with the Advanced Camera on the Hubble Space Telescope. The present SIM design includes astrometric science interferometers with baselines of 10 meters, and guide interferometers with baselines of 8.5 meters. Though the guide interferometers are usable for science observations, they will produce acceptable but reduced phase accuracy. By using data from both baselines and combining observations taken at many small increments in roll angle, SIM can image simple targets over a field of view of ~1" with a resolution (FWHM) of ~0.008" at 500 nm wavelength.

The practical difficulties of doing synthesis imaging of faint targets of arbitrary complexity demand large collectors and a range of interferometer baselines from very short to very long (and many baselines in between), characteristics that SIM unfortunately does not have in its current configuration. However, such instruments promise to provide orders of magnitude in performance improvement over filled-aperture telescopes, and it is likely that space optical/UV/IR telescopes of the future will increasingly be designed to operate in this way. In that case, a clear demonstration of the utility of these imaging techniques using real data obtained from real spacecraft would be of significant importance in spurring the development of future technology. The limitations of the available collector area and interferometer baselines in the current design dictate that the targets chosen for this demonstration be relatively bright and simple in structure.

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