THE SCIENTIFIC BASIS FOR THE SPACE INTERFEROMETRY MISSION

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ABSTRACT

The Space Interferometry Mission is expected to be launched in 2004. The mission, following closely the recommendations of the Bahcall Commission, will determine positions of point sources to an accuracy of 4 μas globally and to 1 μas over small angles ($\leq 1°$). The instrument, based on the OSI architecture proposed by Michael Shao, will reach 20 mag in 3×10^4 sec and has a nominal lifetime of 5 yr. A nulling capability will be provided and synthesis imaging and near-IR capabilities are being considered.

These capabilities, extending the Hipparcos mission by almost three orders of magnitude in every sense, argue for an extraordinary return in scientific results. We expect to challenge our understanding of stellar evolution, to define the nature of the Milky Way in terms of both its global parameters and the various perturbations, to map out the kinematics of the Galaxy's satellites and the other members of the local group and to measure accurate distances to several nearby spirals.

In this paper we will outline NASA's expectations for the scientific return from the SIM mission in the areas of Stellar Physics, Galactic Structure, and Extragalactic Astrophysics including the distance scale problem.

Key words: space astrometry; SIM; space interferometry.

1. INTRODUCTION

With the successful completion of the Hipparcos Mission and publication of the catalogue (ESA 1997), there has been demonstrated the first successful application of the technique of Global Astrometry in space. This remarkably powerful technique breaks the barrier to the most fundamental of all astronomical problems, measuring accurate distances to astronomical objects.

Although Hipparcos is an unqualified success there remains much to be done with particular emphasis on pushing the distance measurements substantially farther and to much fainter limiting magnitudes. With these goals in mind and as a first step in the development of optical interferometry in space, NASA is preparing to enter development of a 'next generation' instrument for this purpose, the Space Interferometry Mission (SIM). In this paper we describe the SIM instrument and its extraordinary scientific range.

2. A BRIEF HISTORY

The progress of SIM towards launch has been marked by three notable events. Although concepts for an advanced astrometric instrument were being actively promoted throughout the 1980's (e.g. Reasenberg et al. 1995 and Shao & Wolff 1992 and references therein), the first milestone occurred when the Astrometric Interferometry Mission (AIM) was recommended as the only major new space start for the 1990's (Bahcall 1991). Responding to this strong endorsement, NASA impaneled the Space Interferometry Science Working Group (SISWG) in 1992 to begin the process of selecting an architecture and defining mission goals.

The second milestone was reached late in 1995 when it became clear that the most productive technique for searching for extrasolar planets would involve a nulling (Bracewell 1978) interferometer of some design. At the same time it was realized that the OSI (Optical Stellar Interferometer, Shao & Wolff 1992) design could be augmented with a nulling capability, allowing it to serve as a critical technology demonstration. This lead to the selection of the OSI as the design for AIM; the addition of a nulling capability in turn lead to the renaming of the experiment as the Space Interferometry Mission. (A summary of the status of the mission and its scientific justification through the spring of 1996 can be found in the final report of the SISWG, Peterson et al. 1996).

The third milestone was occurring even as this paper was being given its oral presentation. In their triennial exercise at setting program priorities and strategies, administrators from NASA's Office of Space Sciences were meeting in Breckenridge, Colorado. The next week it was announced that among other missions, SIM had been recommended for initial design definition study funding (so-called Phase A) starting October 1997. 'New start' status was tentatively set for 2001 with a launch expected in mid 2004. A five year mission was characterized as nominal.

3. SIM: FACTS AND FIGURES

A brief description of SIM as currently conceived is in order. Figure 1 shows in outline the basic spacecraft. On the (10 m) optical bench are mounted 7 siderostats, each of 0.3 m effective aperture. One of these is a spare (but can be used to complete the coverage of the (u, v) plane during synthesis imaging), the other six work in pairs to provide three interferometers operating in Michelson mode. Observations will be made from a 900 km, twilight (sun synchronous) orbit, chosen to minimize solar eclipses ($\leq$ 20minutes, $\leq$ 100days/year).

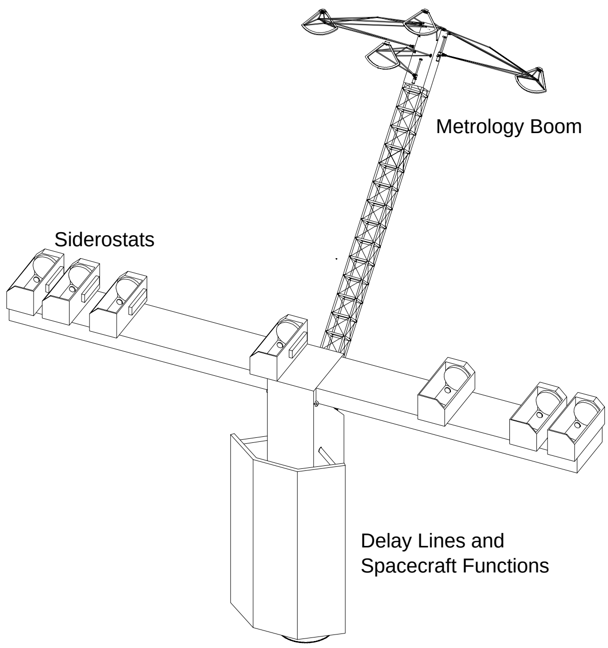

Figure 1. The SIM spacecraft based on the OSI architecture. Six siderostats operate as three pairs of Michelson interferometers. The seventh siderostat is a spare and fills in missing baselines for synthesis imaging.

3.1. Astrometric Operations

At any time two of the interferometers are locked on two fairly bright stars on opposite sides of the (15°) siderostat field of view. During an observation, using these anchor interferometers and star trackers, the orientation of the optical bench is maintained aligned parallel to the two stars while the science interferometer, consisting of the outermost two siderostats, measures the relative separations of the objects in the target field (the 'tile') and the anchors. When this is compeleted (or the orbit requires) the spacecraft orients to another pair of anchors and continues the process. In the end, through overlapping and the use of common anchors, the requirement is imposed that angles along great circles must add up properly and the system 'locks up' (cf. Boden et al. 1997).

Owing to redundancy and the global constraints, we expect the grid to display errors no larger than 2 μas. At this level, grid accuracy will not dominate the 4 μas accuracy, limited by errors not modeled or controlled, that we expect to be the observing floor for the instrument.

There will also be a 'small angle' operating mode, taking advantage of the fact that certain errors can be controlled more reliably over limited motions. Objects within a 1° fields should have their relative locations measurable to 1 μas.

This picture holds for simple positional measurements on objects that show no motion. For real objects additional measures, properly spaced, will determine trigonometric parallaxes, proper motions, and even secular parallaxes for close objects, and others parameters such as those describing orbital motions, if required.

3.2. Throughput

Since SIM is a pointed instrument, not constantly obtaining data as it scans the sky, throughput is greatly limited by pointing maneuvers and settling times. A significant amount of the available observing time must be spent orienting the instrument when moving to new fields. Even when switching targets within a field about 200 sec will be required just to let vibrations damp down. This, the fact that perhaps a third of the 'on target' time will be spent on establishing and maintaining the grid, and the requirement that each object has several parameters that must be defined (position, parallax, motion and secular parallax, plus any orbital parameters), are the primary limits on the throughput of the mission.

The 200 sec settling time corresponds to the time required to make a 4 μas accurate measurement of a 12 mag object (our 'bright' object limit). Correspondingly, we expect to reach this accuracy in about 14 hours at 20 mag, our nominal limiting magnitude. Depending on the exact mix of object magnitudes, we expect to observe about 10^5 science and grid targets in the process of a nominal 5 year mission.

3.3. Nulling

The nulling capability will be implemented in an achromatic fashion, allowing deep nulls at all working wavelengths. However, the width of the central null will scale linearly with wavelength. Current design targets are for a 10^{-4} null to reach 40 μas (diameter) at 5000 Å, with the supression scaling with field angle as $\sin^2\theta$. The first bright ring will have a radius of 5.2 mas at 5000 Å.

3.4. Imaging

The nominal spacing of the siderostats coupled with the ability to rotate the instrument arbitrarily, provides the ability to sample the (u, v) plane over all scales from 0.5 m to 10 m. This gives the instrument the potential to produce synthesis images with resolutions down to 10 mas. In Michelson mode, the field of view is limited by the subaperture diameter - 0.3 m - to about 0.3 arcsec. The very dilute nature of the interferometer greatly limits the number of objects that can be successfully imaged, as will be described below.

3.5. Spectral Sensitivity and Spectroscopy

The nominal detectors will be front illuminated CCDs operating from 4000 Å to 1 μm. Under serious consideration is the possibility of adding a NICMOS type detector, operating in the 1 μm to 2 μm range, either replacing of alternating with one of the CCD. The scientific drivers for such an addition are described briefly below.

The Michelson interferometer must operate with a restricted bandpass (cf. Shao & Colavita 1992); to use the entire spectral sensitivity of CCDs a cross disperser must be introduced. This provides a spectroscopic capability with a resolution of the order of 50. However, on chip summing in the CCD may allow substantially higher resolutions for bright objects.

4. SIM SCIENTIFIC POTENTIAL

The ability to measure absolute parallaxes to 4 μas and proper motions to 1–2 μas yr^{-1} as faint as 20 mag has extraordinary implications for almost every branch of astronomy and astrophysics. We describe below just a handful of the areas where these measurements can have a major impact. In the following it is useful to keep in mind that a parallax to this accuracy returns a distance accurate to 10 per cent out to 25 kpc. Also, a transverse velocity of 1 km s^{-1} at 10 kpc or 100 km s^{-1} at 1 Mpc results in proper motions of 21 μas yr^{-1}.

In this description of the science SIM can provide, we are limited to only a handful of the many areas that will be impacted. A broader overview with many more details can be found in Allen et al. (1997) and particularly in Peterson et al. (1996).

4.1. Galactic Populations

Essentially any object in the Galaxy brighter than 20 mag its distance measured to better than 10 per cent and its transverse velocity to 1 km s^{-1} accuracy (limited by the parallax in most cases). The implications include:

- Luminosity calibrations for every identified group of objects: Subject to the 20 mag limit, SIM will determine distances to members of all identifiable groups in the Galaxy and will allow calibration of not only the luminosities, but also the extent of metallicity and age effects. Members of clusters will play a particularly significant role in this respect.
- Distances to Galactic and globular clusters: Accurate distances to a variety of clusters will represent the greatest challenge to stellar evolution theory since models first were calculated in the 1950's.
- Distances to binary star systems: The increase in our knowledge of the mass function will be dramatic. Members of clusters with known ages and compositions will be particularly important. Double and triple systems containing stellar-mass Black Hole candidates will provide strong mass constraints, perhaps even direct determinations.
- The photometric-based distance scale: As examples of the importance of calibrating luminosities and masses, we will for the first time have a good determination for the massive OB, AF and M supergiants, objects which can be identified in galaxies over tremendous distances. Also, various period-luminosity relations, notably for the Cepheids and the RR Lyra stars, will be calibrated using potentially every known member of these groups. Again, cluster members will play particularly important roles.
- Detection of extrasolar planets: SIM will do an extraordinary job of searching for planetary sized objects orbiting nearby stars. It is sensitive enough in 'narrow angle' mode to detect the Earth orbiting the Sun at 5 pc. Jupiter's signature would be detectable at 8 kpc . It is capable of at 7–10 times better accuracy that the best proposed ground based astrometric detection scheme for systematically searching nearby stars. And, of course, astrometric detection is the only technique that determines companion masses directly, an extremely critical parameter.
- Spectroscopy of substellar companions: Several of the recently detected low mass companions of nearby solar type stars have very small separations; for example, the companion of 51 Peg is at a separation of 0.05 AU (Marcy & Butler 1996). Even if these companions are near or at their minimum masses, they should be in thermal equilibrium with their primaries (Burrows et al. 1995), and thus will emit significantly on their own. Operating in nulling mode, direct detections and diagnostic spectroscopy (Marley et al. 1996) could be obtained with a near IR detector. Even with only CCD sensitivities, the lack of a detection would put strong upper limits on any self-luminosity.
- Dynamics of small systems: One intriguing problem is to understand the dynamical evolution of globular clusters (and dwarf spheroidal galaxies, see below). Current modelling suggests that as these systems evolve the motions of the stars near the centers tend to be more radial than isotropic. This could be easily resolved through proper motion measurements of stars in or near the cores of these systems. Simulations indicate that synthesis imaging of a finite number of unresolved (by a subaperture) point sources incurs only a slight penalty compared to direct observation. Guided by HST images, observations of the cores of a range of globular cluster types could be made in order to analyze core orbital characteristics.

4.2. Structure of the Galaxy

Even more far reaching is SIM's potential to revise our understanding of the Galaxy. This will occur on several fronts, including the kinematics and spatial distribution of the various subsystems and the dynamics and mass distribution of the system overall. Indeed, given the basic, 25 kpc reach of the instrument, it is arguable that the Galaxy above all is its natural target (and, given the amount of obscuration in the plane, this is one of the strongest argument for a near IR capability).

Specific problems that will be addressed include:

- Determination of the true distribution of stellar types: This would bear directly on the dynamical and chemical evolution of the Galaxy. Particularly important will be the characterization of the inner bulge component.

- Determination of the gravitational potential: This includes both probing the Z-dependence of the gravitational field at the solar location *and* at other locales as well as evaluating the rotation curve, particularly outside the solar radius. The distances and total motions of the globular clusters will play a major role here.

- Characterizing rotational symmetry: There is plenty of historical evidence that the Galaxy is not perfectly rotationally symmetric, and modern observations point to additional structure. SIM will begin the process of characterizing the amplitude of such effects as spiral arm mass enhancements, warps and twists of the plane, and the size and orientation of the recently discovered inner bar.

- $R_\circ$: With the large list of modes by which the Galaxy can deviate from circular symmetry, it is no longer possible to rely on simple dynamical analyses to determine the distance to the Galactic center. Moreover, the lack of a definitive value for $V_\circ$ creates the same problem in using proper motions at the Galactic center to derive $R_\circ$. SIM, augmented with a near IR capability, would be able determine this critical parameter to 3 per cent. That coupled with an order of magnitude improvement in the proper motions compared to the current water mazer observations, would provide corresponding accuracy in $V_\circ$.

- The Sagittarius dwarf and the Galactic halo: There is now evidence that the recently discovered Sagittarius dwarf galaxy that is plunging through the plane on the opposite side of the Galaxy, sports a tidal tale extending 80° across the sky (Ibata, Gilmore & Irwin 1995, Ibata 1997). A complete characterization of the geometry and dynamics of that debris would provide the most complete probing of the Galactic potential in the tens of kpc range, currently available. Again, this is exactly what SIM is best at.

4.3. Extragalactic

With the probable exception of the Sagittarius dwarf, extragalactic objects will be out of range for accurate parallax measurement. However, so long as objects can be found in the systems brighter than 20 magnitude, transverse motions can be measured. This still leads to a remarkably rich collection of scientific problems.

- The Magellanic Clouds: Possibly the one exception to the above statement are the Magellanic Clouds. If measurement errors can be controlled at the 2 μas level, 10 per cent distances could be obtained for the two systems. Considering the amount of research on these objects already in the literature, this would have an instantaneous impact. In addition, accuracy at that level would resolve the depth of the systems, yielding important insight into their structure and status. Even with the nominal parallax accuracy, tidal debris trails tentatively identified would be readily confirmed.

- The Local Universe: Any galaxy with a significant Pop I component, i.e. the later type systems, would be expected to have a population of massive supergiants that could be seen out to 3–4 Mpc (absent absorption). Proper motions corresponding to accuracies in transverse velocities of a few tens of km s^{-1} could be obtained. These would materially contribute to our understanding of the kinematics of this part of the Universe, as well as the age of the Local Group.

- Milky Way Satellites: By the same token, bulk proper motions could be obtained for the dwarf spheroidal satellites of the Milky Way. This would provide yet another probe of the Galaxy's potential, only now out in the 100–300 kpc regime. Further, a clear measurement of the velocity dispersion of these systems could be made, substantially focusing the issues of total mass and fraction of non-luminous matter.

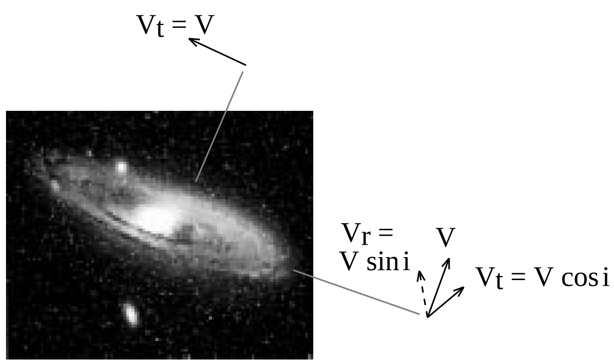

Figure 2. The circular rotation of M31, analyzed. Since proper motions depend inversely as the distance, measuring the proper motions of stars on the major and minor axis along with the latter's radial velocity, will yield the velocity curve and the dynamical inclination as well as the distance.

- Large Nearby Spirals: One exciting possibility whereby SIM may leverage accurate distances to the major nearby spirals, involves matching measurements of the projected circular rotation in both proper motion and radial velocity. The situation as it would apply to M31 is shown in Figure 2. Proper motions nominally measured along the major and minor axes and the radial velocity on the major axis (in practice, motions along all directions would be modeled) could be combined to deduce the distance (as well as dynamical parameters). We estimate that distances good to better than 10 per cent could be deduced for the local group galaxies M31 and M33, for the distant M81 and for 3 or 4 other systems showing circular rotation. Distances to other nearby systems could also be obtained this way, but with some dependence on parameters derived by other techniques.

- AGN: In synthesis imaging mode SIM may be able to make substantial contributions to our knowledge active galactic nuclei (AGN). One example, shown in Figure 3, is the nucleus of NGC 4261, where imaging and spectroscopy by the Hubble Space Telescope has made a strong case for a disk revolving around a massive Black Hole. SIM has the potential to improve on the resolution in this image by nearly a factor of ten. However, to illustrate the difficulties, even in this fairly favorable case, 24 hours total observing in synthesis mode would provide a S/N of only 5 per pixel over the core.

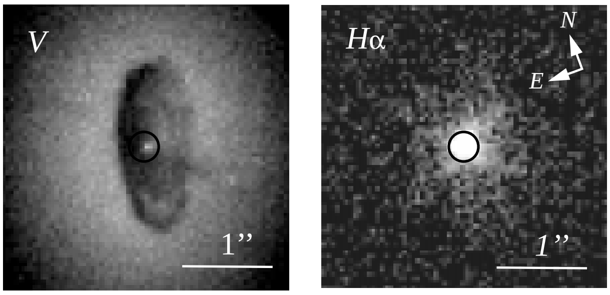

Figure 3. NGC 4261 appears to contain a $10^9\,\mathrm{M}_\odot$ *Black Hole. The HST image shown here (courtesy L. Ferrarese) barely resolves the nucleus at 0.12 arcsec. SIM can provide ten times that resolution. The SIM field of view, 0.3 arcsec, is shown.*

- General Relativity: Under a miscellaneous heading, SIM has the potential to substantially improve testing the prediction of the deflection of light by the Sun. Moreover, the instrument will be so sensitive that account will have to be made for the deflection effects of Jupiter and the other massive planets.

5. CONCLUSIONS

SIM is an instrument of extraordinary potential. It holds the promise of revitalizing stellar astrophysics, of defining finally the Galaxy we live in, of characterizing the three dimensional kinematics of galaxies in and near the Local Group for the first time, and of directly skipping five or six steps on the ladder to calibrate the Hubble constant.

Beyond that, SIM will represent the first real spatial interferometer flown in space. As such the technology challenges are huge. In turn, SIM's role as a technology precursor for future interferometry missions seems the key to securing its place in NASA's mission queue. At this point there is reason for great optimism.

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