1 Executive Summary

This SIM Key Science program will produce important research on SIM grid objects that directly relate to the stability of the SIM reference frame. It will accomplish this by making efficient use of observations of the quasars that will be used for the purpose of establishing a link between the SIM reference frame and the International Celestial Reference Frame (ICRF). In addition, we propose to use 1% of the total SIM time (approximately 250 hours over the lifetime of the mission) to observe a limited number of galactic radio sources that will not be part of the SIM/ICRF frame link, but can be used as a consistency check of the extragalactic frame tie. Through these observations we hope to deliver the maximum amount of science for a limited amount of SIM resources. This SIM Key Science project will achieve the following objectives:

1. We will analyze SIM data taken on stars previously observed by the Full-sky Astrometric Mapping Explorer (FAME) to search for local and global systematic frame offsets. A detailed study of FAME stars will allow us to exclude stars with known irregular motions from the SIM astrometric grid. These “problem” stars from the FAME observations will make excellent targets for further study by SIM. In turn, improved observations of FAME stars by SIM will provide us with a better calibration of the FAME astrometric grid.

2. We will analyze all SIM data taken on all SIM/ICRF frame tie sources to search for systematic radio/optical position offsets. These observations and the subsequent analysis will allow us to determine whether the optical emission is an extension of the radio synchrotron flux or is generated by some other mechanism. We will analyze all SIM observations of extragalactic sources to search for optical photocenter wander. A global analysis of photocenter wander will provide invaluable insight into the origin of the optical emission in quasars.

3. We will provide the SIM project an improved list of high astrometric quality ICRF quasars suitable for anchoring the SIM astrometric grid and for tying the SIM reference frame to the ICRF with the highest possible precision. We will work closely with the SIM project team to ensure the highest quality radio/optical link possible, thus enabling the most interesting astrophysics.

4. We will investigate the astrophysics of chromospherically active stars (both isolated and binary radio stars) through observations of ~100 of these objects using SIM in the wide-angle astrometry mode. We will register the continuum radio emission, as measured by the Very Long Baseline Array (VLBA) and/or the Very Large Array) VLA, to the stellar positions as determined by SIM. For the active stars in binaries we will determine whether the radio emission is located near the surface of either of the stars or in the intra-binary region. In addition, SIM observations of radio stars will provide a verification of the SIM extragalactic frame tie.

5. We will investigate the transition of spherically symmetric asymptotic giant branch stars to asymmetric planetary nebulae. We will observe ~100 asymptotic giant branch stars, which have spectral-line radio emission, using SIM in the wide-angle astrometry mode. The maser emission from these objects provides a tracer for asymmetry in the circumstellar envelopes. SIM observations will provide the distances and photocenter positions necessary to distinguish between competing models of asymptotic giant branch stellar evolution.

Since this proposed Key Science program will require less time than a full Key Science project, the required funding resources have been appropriately scaled. The principal costs of this proposal are direct labor costs of the principal investigator and the co-investigators. We have budgeted \$10K in the first year for computer equipment with provisions for upgrades every three years. In addition, we have budgeted \$15K per year for travel. In support of the Southern Hemisphere Very Long Baseline Interferometry (VLBI) program we anticipate two trips annually to the Australia Telescope National Facility (ATNF) throughout the 11 program years. Finally, \$6K per year has been allocated for publication charges. Results from the Key Science project including preparatory work will be published in refereed journals. Subsequent years in the budget have been adjusted 3% per year for inflation.

2 Key Science Project Goals

2.1 Introduction

SIM expects to use an all-sky astrometric grid, consisting of several thousand stars, for astrometric instrumental calibration and to perform wide-angle (or global) astrometry. To the extent that SIM is an astrometric mission, the all-sky astrometric grid is the cornerstone of mission operations. Among the reference objects, SIM has plans to observe numerous extragalactic objects (nominally quasars) to establish a quasi-inertial anchor for the all-sky astrometric grid. Although these extragalactic sources need not be radio-loud, use of suitable radio-loud ICRF quasars for this purpose (in addition to providing a link to the ICRF) will minimize SIM calibration overhead. Currently, the ICRF will limit the accuracy of a SIM/ICRF frame tie if the projected accuracies for SIM are realized. One of the goals of this Key Science program is to determine the ultimate accuracy to which radio and optical astrometric observations can be made, thus enabling the most accurate radio/optical link feasible. This will allow the precise overlay of the radio and optical emission structures associated with the science targets of this Key Science proposal. Additionally, the proposed work will provide the SIM project an improved list of high astrometric quality ICRF quasars suitable for anchoring the SIM astrometric grid and for tying the SIM reference frame to the ICRF with the highest possible precision. SIM must make observations for the derivation of the extragalactic tie. Extragalactic objects brighter than $m_V = 20$ must be observed over the life of the mission in order to determine the orientation and the rotation of the SIM grid with respect to the ICRF (Final Report of the SIM Science Working Group - 2/25/00, p. 46; http://sim.jpl.nasa.gov/ao_support/simswg_report.html). We will work closely with the SIM project team to ensure the highest quality radio/optical link possible, thus enabling the most interesting astrophysics.

The following proposal describes the science we wish to do with SIM and the prepatory work necessary to meet these goals prior to the launch of SIM. The U.S. Naval Observatory (USNO) is in a unique position to conduct the work proposed herein. The mission of the USNO is to determine the positions and motions of celestial objects, the motions of the Earth, and precise time. In pursuing its mission, the USNO routinely produces astrometric catalogs and conducts observations of celestial objects at a variety of observing wavelengths, including optical, infrared, and radio. Using the technique of VLBI, the USNO has a long-term involvement in observing programs responsible for formulating both the celestial and terrestrial reference frames. A catalog of the radio positions of a large number of extragalactic sources distributed over the entire sky was presented by Johnston et al. (1995). This catalog, and its successor, the ICRF, marked a milestone in defining a global, self-consistent, quasi-inertial celestial reference frame. USNO personnel, including the authors of this proposal, were among the contributors to the definition of the ICRF and coauthors of the refereed publication presenting the catalog (Ma et al. 1998). The ICRF has been adopted by the IAU as the fundamental celestial reference frame, serving as the basis for all astronomical reference frames at any wavelength. Finally, our inherent connection with the FAME mission will serve as an invaluable aid in both the quality of the proposed Key Science project and in the verification of SIM astrometric capabilities.

2.2 FAME/SIM Synergy

The Full-sky Astrometric Mapping Explorer (FAME) is a survey mission and will make astrometric position measurements of order 40 million objects with a precision of 50 μas for objects with $m_V < 9$. Much like Hipparcos, FAME is based on the use of a telescope that looks at two fields of view (FOV) separated by a fixed basic angle (81.5°). The spacecraft rotates at a rate of once every 40 minutes and measures stars along a spiral. The rotation axis of the spacecraft precesses around the Sun direction 18.3 times a year to scan the whole sky. Unlike Hipparcos, which used an image dissector tube, FAME will use a CCD array with high quantum efficiency to determine transit times while simultaneously observing many stars. With a limiting magnitude of $m_V = 15$, the FAME mission will be capable of observing only the brightest extragalactic sources. The FAME tie to the ICRF will be accomplished mostly through radio star observations such as was done for Hipparcos (Lestrade et al. 1995) but a weighted solution using observations of both extragalactic objects and radio stars will probably be used to produce the optimal alignment.

SIM is planned as a pointed mission with a limited number of target objects (on the order of 10000) with approximately 4 μas positional accuracy for objects with $m_V < 20$. Construction of the SIM astrometric grid involves linking adjacent astrometric “tiles”, where a tile is defined as the set of stars observed within the SIM field of regard (FOV with a diameter of 15°). Tiles will be linked together by stars in the overlap regions, thereby covering the entire sky with a systematic, interlaced, brickwork-like pattern of discrete pointings.

The high precision FAME positions, parallaxes (<10% for $m_V < 9$ objects within 2.5 kpc of the Sun), and proper motions will serve as an excellent input catalog for SIM, reducing calibration overhead for reduction of the SIM astrometric grid. FAME data will also provide invaluable insight to SIM on the effects of asymmetric brightness distributions, such as star spots, on the astrometric position determination of stars at the tens of microarcsecond level. Similarly, FAME data can be used to assess the optical compactness of candidate SIM/ICRF quasars.

Through the use of the FAME astrometric grid, SIM observations can be aligned to the ICRF early in the SIM mission, reducing SIM calibration overhead for science targets. Since the methods of construction of the astrometric grids for both the SIM and FAME missions are fundamentally different, the final FAME and SIM grids can be aligned, compared, and analyzed for systematic differences and zonal errors. An analysis of this nature will serve as an invaluable consistency check for both the SIM and FAME missions.

Additionally, systematic differences or zonal distortions between the FAME and SIM astrometric grids can be used to search for astrophysically interesting phenomena that would not otherwise be possible. For example, local distortions between the two frames could be indicators of gravitational lensing events due to e.g. Massive Core Halo Objects (MACHOs). There are several hypotheses concerning the nature of these objects ranging from compact objects such as Jupiter mass planets or small stars (brown and white dwarfs) to non-compact objects such as non-baryonic dark matter. High precision astrometric observations will allow determination of the physical parameters of these objects, which in turn will lead to a better understanding of their physical nature. SIM/FAME frame comparisons may lead to detection of lensing events that would otherwise go undetected in the individual frames due to e.g. an insufficiently long time baseline.

The FAME mission will be able to measure the parameterized post-Newtonian (PPN) γ to a few parts in 10^5. SIM will be able to measure γ to a few parts in 10^6. Deviations of the parameter γ from unity are a way of testing the validity of scalar tensor gravitational theories. The accuracy of both FAME and SIM will require a relativistic treatment of light propagation as well as a relativistically correct treatment of the celestial bodies of the solar system. A comparison of the estimated value of the parameter γ from the FAME and SIM missions will serve as an invaluable consistency check for both missions.

2.3 Quasar Science

The unprecedented astrometric accuracy and brightness sensitivity of SIM (~4 μas for $m_V<20$) will allow, for the first time, the determination of the optical positions of extragalactic objects at the microarcsecond level, thus enabling a direct connection between the stellar and extragalactic frames. A direct and accurate link between the ICRF and SIM frames will allow many scientifically interesting comparisons between multi-wavelength observations of specific objects, and comparisons between SIM catalogs and objects in catalogs made with other instruments. Alternatively, the FAME mission will be limited to position precision of ~500 μas for objects with $m_V \approx 15$. The median visual magnitude of ICRF quasars is $m_V \approx 18$. In the next two sections we discuss the astrophysical investigations we propose to perform using the SIM observations of extragalactic sources.

2.3.1 Coincidence of Radio/Optical Photocenter

In the standard theory of extragalactic radio sources (e.g. Blandford and Konigl 1979), emission from quasars and active galactic nuclei is assumed to be powered by a central engine (presumably a black hole) where energetic phenomena occur. Extragalactic radio sources are known to have frequency dependent intrinsic structure, usually consisting of a flat spectrum core ($S \propto \nu^\alpha$, where $\alpha \approx 0$) with extended emission in the form of multiple steep spectrum ($\alpha \approx -0.5 \sim -1.5$) jet components which may move superluminally away from the core (superluminal motion is motion perpendicular to the line of sight with an apparent linear velocity in excess of the speed of light).

Opacity changes in the core regions of extragalactic objects may produce frequency dependent changes in the position of the peak emission of the core, presumably along the position angle of the jet emission. In the standard relativistic jet model (Blandford and Konigl 1979), the core is the base of the jet where the optical depth is approximately unity. The position of the core should then be further downstream at lower frequencies. This has been observed for the case of the quasars 1038+528 A & B. From phase-referenced observations, Marcaide & Shapiro (1984) found a frequency dependence of the position of the core of A with respect to B of the order 0.7 mas between 13 and 3.6 cm wavelength with the smaller separation being at 13 cm. Marcaide & Shapiro (1984) suggest that the position shift of the radio emission between 13 and 3.6 cm wavelength is probably intrinsic to the A source.

The origin of optical wavelength radiation from extragalactic objects identified with compact radio sources is not well established. If the optical emission is an extension of the radio synchrotron flux, then the optical emission should come from a region closer to the central engine than that of the radio emission. This optical depth effect should then lead to a systematic offset between the measured radio and optical positions of a quasar. If we assume that the position of the quasar photocenter is proportional to the wavelength of observation raised to the power β, then for the case of the quasar 1038+528 A discussed above, the radio position should be offset from the optical position by approximately 0.3 mas, assuming a value of $\beta = 1$ (Marcaide & Shapiro give a range of $0.7 < \beta < 2$). Optical identification and spectra show 1038+528 A and B to be quasars with $m_V \sim 17.5$ and ~18.5 and z = 0.678 and z = 2.296, respectively. The astrometric accuracy of the ICRF positions of 1038+528 A and B are 0.3 and 0.6 mas, respectively.

We propose to analyze all SIM data taken on all SIM/ICRF frame tie sources to search for systematic radio optical position offsets. These observations and the subsequent analysis will allow us to estimate the value of β and determine whether the optical emission is an extension of the radio synchrotron flux or is generated by some other mechanism. To our knowledge, the source 1038+528 A is the only source where the optical depth position offset has been measured in the radio regime. However, observation of systematic position offsets between the radio and optical emission in ICRF quasars will provide invaluable insight into the physical mechanism(s) generating the radio and optical emission. Presumably, the position offsets will be along the jet direction, which can be estimated from radio imaging observations. Absolute positional astrometry is required for a comparison of this nature. Due to uncertainties in the spatial extent of the optical structure of extragalactic sources on microarcsecond scales, the absolute accuracy to which SIM optical positions of ICRF sources can be measured is not yet known. Microarcsecond accuracy would be ideal but due to limitations in SIM sensitivity (most ICRF quasars have optical magnitudes between about m_V= 16–19), optical positions on the order of 20–30 μas would be acceptable since the radio positions will be the limiting factor in the comparison. However, additional radio astrometric observations are required to refine the positions of candidate SIM/ICRF frame tie sources to be able to measure the offset between the radio and optical photocenters as accurately as possible since the actual offsets are unknown and will most likely be different from source to source.

2.3.2 Optical Photocenter Wander

We propose to analyze all SIM observations of extragalactic sources to search for optical photocenter wander. A global analysis of photocenter wander will provide invaluable insight into the origin of the optical emission in quasars. For example, optical photocenter wander can be used to search for binary black hole signatures. We propose to search for the effects of binary black hole orbits on the positions of quasar photocenters and thus test the hypothesis that binary black hole mergers are responsible for most quasars (e.g. Gould & Rix 2000). A positive detection of binary black hole induced motions in ICRF quasars would be good evidence to support this hypothesis. For example, the source OJ287 is thought to contain a binary black hole with an orbital period of 12 years, a semi-major axis of 0.06 pc, and a primary to secondary mass ratio of about 170 (Lehto & Valtonen 1996). At a redshift of 0.306, the semi-major axis corresponds to an angle on the sky of about 22 μas (assuming H_0 = 100 km s^{-1} Mpc^{-1} and q_0 = 0.5). Motion within a region of this size could be very easily detected by SIM. If the emission of OJ287 comes from a narrow cone centered on the axis of the accretion disk of the primary (i.e. the optical emission is an extension of the radio synchrotron flux) then little photocenter wander would be expected. If the emission comes directly from the accretion disk (either the primary or the secondary) then some (unknown) degree of photocenter wander would be expected. If, for example, the emission comes from the accretion disk of the secondary, then over the 5 year lifetime of the SIM mission, a rough estimate of the maximum change in the optical position of OJ287 due to the orbital motion of the binary black hole would be on the order of (5/12) × 44 μas =18 μas. Another example would be for the source 3C390.3. This source is thought to contain a binary black hole with an orbital period of 300 years, a semi-major axis of 0.3 pc, and a primary to secondary mass ratio of about 2 (Gaskell 1996). At a redshift of 0.057, the semi-major axis corresponds to an angle on the sky of about 300 μas (assuming H_0 = 100 km s^{-1} Mpc^{-1} and q_0 = 0.5). Motion within a region of this size could definitely be detected by SIM.

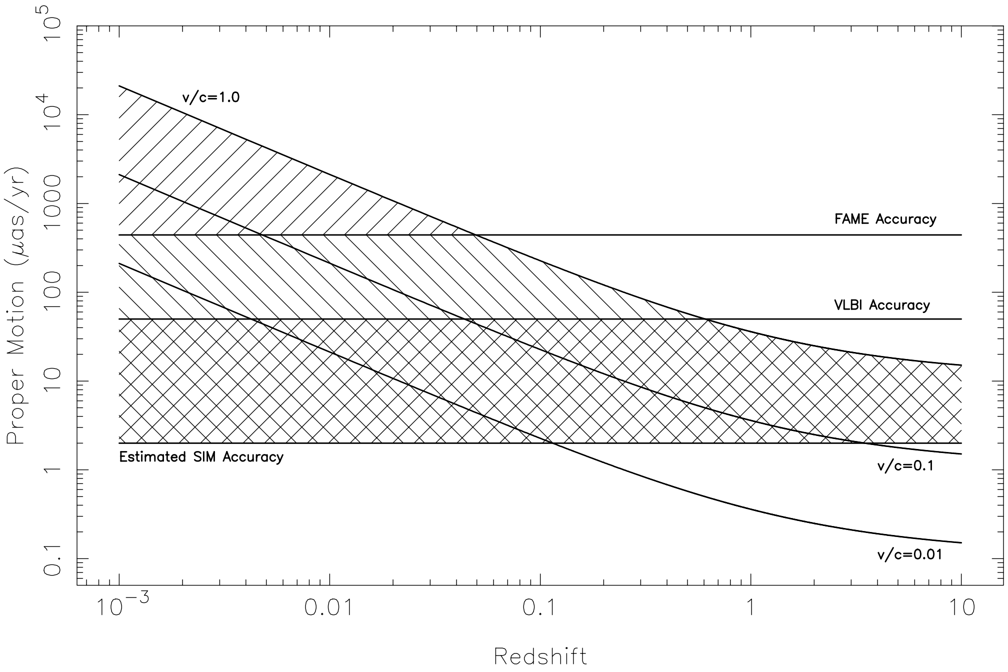

Figure 1 Proper motion redshift relation (assuming H_0 = 100 km s^{-1} Mpc^{-1} and q_0 = 0.5) for objects with the indicated transverse velocities. Horizontal lines represent the estimated accuracy of astrometric VLBI and the expected accuracy of SIM. The hatched areas indicate the range of parameter space sensitive to the various instruments.

Optical photocenter wander can also be used to place upper limits on quasar proper motions. Limits on quasar proper motions can be used to constrain theories in which the redshifts of quasars do not indicate cosmological distances but rather suggest that they are local and have high Doppler redshifts (e.g. Narliker & Subramanian 1983). Shown in Figure 1 is the expected proper motion as a function of redshift for relativistic motion transverse to the line of sight. If quasars were close (e.g. 100 Mpc) and moving at relativistic velocities (v/c ≈ 1) they would have proper motions on the order of several hundred microarcseconds per year. VLBI astrometric observations (taken over 20 years) are sensitive to proper motions greater that about 50 μas/year (Ma et al. 1998). This is shown as the center hatched area in Figure 1. The median redshift of the distribution of ICRF sources is about z = 1. Thus VLBI is sensitive to proper motions of only the fastest and closest sources. Observationally, only a handful of sources have statistically significant proper motions. Since these motions translate into apparent velocities of 3-5 times the speed of light (assuming the redshift is cosmological), they are assumed to be caused by structure variations in the radio emission. SIM will be able to measure proper motions more than a factor of 25 times better than VLBI. SIM will extend proper motion sensitivity into the cross-hatched region shown in Figure 1 and should allow us to place very tight constraints on the distances to quasars.

2.4 Stars with Radio Continuum Emission

Stellar radio sources come in a wide variety of classes including: RS CVn binaries, eclipsing Algol-type binaries, x-ray binaries, novae, pre-main sequence stars, ultra-fast rotating G and K stars, pulsating variables, cataclysmic variables, and various sources with strong stellar winds. The primary question in the study of radio stars is the location of the radio emission with respect to the optical emission. At optical wavelengths, the Hipparcos Catalog currently serves as the primary realization of the extragalactic reference system. The Hipparcos Catalog link to the ICRF was accomplished, primarily, through VLBI observations of 12 radio stars (Lestrade et al. 1999; Kovalevsky et al. 1997). Unfortunately, the errors associated with the Hipparcos/ICRF link are still too large to enable milliarcsecond level astrometry between radio and optical images.

As part of this SIM Key Science Proposal, we plan to use SIM observations of radio stars in conjunction with an established VLBA/VLA observing program to investigate the astrophysics of these objects. We propose to observe ~100 radio stars, which will be selected for both optical and radio continuum brightness, using SIM in the wide-angle astrometry mode. Since these objects are bright ($m_V < 10$ in most cases), to achieve the desired accuracy of 10 μas, we will require approximately 0.6 hours of mission time per source or a total of 60 hours to do all 100 radio stars. Roughly half of the radio stars we propose will be active binaries. These binaries will require additional observing time since we wish to determine an additional 7 orbital parameters. These binaries will require at least 24 1-d observations, and to build in a margin of safety, we propose to increase the minimum number of 1-d observations from 20 to 50 observations. This will add an additional 40 hours of mission time bringing the total to ~100 hours. The following three sections describe the scientific investigations we propose to do, and the benefits of determining accurate positions, proper motions, and parallaxes for a set of stellar radio sources.

2.4.1 Optical/Radio Reference Frame Links

Traditionally, links between the radio and optical frames have been determined through observations of radio stars. As mentioned above, the link between the ICRF and the Hipparcos Catalog was accomplished through VLBI observations of 12 radio stars. SIM observations of the radio stars will provide a much more accurate tie between the two frames, and will be limited only by the accuracy of the radio positions of the stars. We hope to improve the accuracy of the radio positions through an extensive VLA/VLBA observing program described later in the Preparatory Science sections. Although the frame tie between SIM and the ICRF will be accomplished through observations of extragalactic objects, the tie between the FAME grid and the ICRF will rely on observations of radio stars. Observations of radio stars in the FAME catalog by SIM will both extend and calibrate the FAME measurements. Walter, Hering, & de Vegt (1997) have compiled a catalogue of 66 objects with declinations greater than –30° which they dubbed “cardinal radio stars for linking celestial reference frames”. We plan to include most of these cardinal radio stars in our list of proposed objects for observation by SIM. In addition, these objects will be observed by FAME. SIM observations will help us to determine the optical astrometric stability of these cardinal radio stars and their applicability to the SIM/FAME/ICRF frame ties.

2.4.2 Observations of Chromospherically Active Binary Stars

The study of active binary stars will benefit significantly from an improved radio-optical link resulting from combined radio/SIM observations. For example, no consensus has yet developed concerning the physics of the formation and evolution of the radio emission associated with these active binary star systems. For most active binaries, the location of the radio emission with respect to the binary components is unknown; i.e. 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.

We propose to use SIM in conjunction with the VLBA and the Navy Prototype Optical Interferometer (NPOI) to fully investigate the astrophysics of RS CVn and Algol-type binary systems. These three instruments all have complimentary capabilities. With the VLBA we will be able to determine the location of the radio emission to 200–300 μas accuracy. Since these RS CVn and Algol-type binaries are close (1–10 mas in general), SIM with its 10 mas resolution will not be able to resolve the individual stars in the binary. With an imaging resolution of ~200 μas the NPOI will allow the determination of the location of the component stars, their magnitudes, their sizes, and their orbital parameters. Unfortunately, the NPOI will only be able to determine the absolute position to within ~3 mas, thus SIM will complete the picture by accurately determining the absolute position of the optical photocenter. Once the NPOI is fully operational, magnitude limit will be $m_V \approx 8$. Some fraction of the chosen radio stars will be too faint for observation by the NPOI. For these stars the orbits will have to be determined spectroscopically (see for example the Catalogue of Chromospherically Active Binary Stars; Strassmeier et al. 1993). SIM will be able to determine the inclination of the orbit for the spectroscopically observed stars and the registration of the radio and optical photocenters.

This project is ideal for SIM since a pointed mission is required for observation of short time-variable phenomena. Since these stars have very short periods (between 1 and 20 days for the majority), the observations must be conducted in two phases. To accurately determine the position, proper motion and parallax of each binary, 20 1-d observations should be spread over the 5-year SIM mission. To determine the 7 orbital parameters through observations of the wander of the optical photocenter, an additional 30 1-d observations (margin of safety built in) should be conducted over one orbital period (1–20 days). Due to the fact that FAME is a scanning mission, and will not return to a source in less than ~20 days, the determination of the orbit for these active binaries with FAME will be nearly impossible.

2.4.3 Isolated Chromospherically Active Stars

SIM observations of the isolated chromospherically active stars in our proposed observations should provide equally interesting results. Like the active binary systems, these stars suffer from a lack of knowledge of the position of the radio emission relative to the stellar optical photocenter. For these stars, the registration should be easier since there is no companion. There is the possibility that we would detect large star spots that are possibly related to the radio and x-ray emission in these objects. Observations of these stars may be coordinated with FAME, especially for input positions, proper motions, and parallaxes, but FAME will probably not be able to detect the photocenter wander due to star spots as observed by SIM.

2.5 Stars with Spectral-Line Radio Emission

Asymptotic Giant Branch (AGB) stars represent an important stage in stellar evolution. Most AGB stars are categorized as long-period variable (LPV) stars, which include semi-regular variables, Mira variables, and OH/IR stars. Approximately 90% of the stars classified as long-period variables are oxygen-rich M-type AGB stars many of which exhibit one or more of the three “classical” maser species: SiO, H_2O, and OH. Lewis (1989) presents a chronology of oxygen-rich, LPVs classified according to the types of maser emission present in the star’s circumstellar envelope. Table 1 shows the various stages in the AGB phase of stellar evolution and the types of maser emission associated with each phase.

We propose to observe a sample of ~100 LPVs with circumstellar maser emission using SIM. Since SIM is an optical interferometer, it will not be able to sample the full range of chronological stages presented in Table 1. The OH/IR stars, which begin around stage 4, have thick circumstellar dust shells, which obscure the visible light from the star. Stages 1 through 3 represent the semi-regular variables and the Mira variables, which are observable using SIM. In these early stages, SiO, H_2O, and main-line (1665 and 1667 MHz) OH maser emission are seen in many of the sources. In addition, there are a few Mira variables with satellite-line (1612 MHz) OH maser emission, which lie somewhere between stages 3 and 4 in Table 1.

Table 1 Summary of Chronological Stages (Lewis 1989)

Stage	Key Change	SiO	Water	Main	1612	Note
1	SiO masers	Y	N	N	N	
2	Add water	Y	Y	N	N	
3	Add 1665/7	Y	Y	Y	N	
4	Add 1612	Y	Y	Y	Y	Type I
5	Main weaken	Y	Y	Y	Y	Type II
6	Lose 1665/7	Y	Y	N	Y	
7	Lose water	Y	N	N	Y	
8	Lose SiO	N	N	N	Y	PPN's
9	Add 1665/7	N	N	Y	Y	Type II
10	Main strong	N	N	Y	Y	Type I
11	PN stage	N	N	N	N	Usually

All of the science we wish to do can be accomplished using SIM in the wide-angle astrometry mode with astrometric accuracies on the order of 10 μas. Since Miras are pulsators with mean magnitudes around $m_V \approx 11$ and variations of $\Delta m_V \approx 6$, then to achieve 10 μas astrometric accuracy throughout the stellar cycle would require the minimum 20 observations per source (approximately 0.7 hours of mission time per source) or 70 hours to do all 100 sources. These observations would allow us to solve for the five parameters: position in right ascension and declination, proper motion in R.A. and declination, and parallax. In addition we would also like to look for signatures of binaries around these AGB stars (see section 2.5.1 below), which requires solving for an additional 7 parameters or 24 1-d SIM observations. Doubling the minimum number of SIM observations to 40 1-d observations (~1.4 hours of mission time) for each source should allow us to solve for all 12 parameters with a built in margin of safety. To do ~100 proposed stars would then require a total mission time of approximately 140 hours. It may be possible to coordinate SIM observations of LPVs with FAME observations of the same stars, especially if FAME could provide a baseline for the positions, proper motions, and parallaxes. However, FAME will not have the astrometric accuracy to enable searches for non-radial pulsations or hidden binary companions (section 2.5.1 below).

Since LPVs are large red giants and supergiants, the possibility that SIM may resolve-out the desired target sources must be considered. Assuming a typical Mira radius of about 450 solar radii (3.2×10^{13} cm) and the proposed 10 mas resolution for SIM, then the observed variables must be at a distance greater than about 200 pc. For this proposal, target source selection will therefore be limited to Mira and semi-regular variables further than this 200 pc limit. LPVs closer than this distance, or with known radii larger than this typical value, will be interesting targets for SIM if one could map the optical emission in a particular SIM spectral channel. It may then be possible to observe the asymmetries in these stars as was done by Karovska et al. (1997) for o Ceti using HST. There are several important astrophysical questions we hope to answer through the proposed SIM observations of semi-regular and Mira variables with maser emission. These questions are discussed in the following four subsections.

2.5.1 Asymmetry in Circumstellar Envelopes

One of the most intriguing questions in stellar astrophysics is the apparent transition of spherically symmetric AGB stars to planetary nebulae, which are asymmetrical, often elliptical or bipolar. The shaping of planetary nebulae (PNe) is a well-studied topic, and models based on the interacting winds model (e.g. Weaver et al. 1977; Kwok et al. 1978) have had considerable success in explaining PNe morphologies. In this model, a fast wind is ejected from the hot central star of the PNe, which overtakes the slower circumstellar envelope previously ejected during the late stages of the AGB phase (Soker & Livio 1989). The more asymmetric PNe are modeled by giving the slower AGB wind some form of axial symmetry through a density contrast between the equatorial and polar regions of the envelope. Still, two fundamental questions remain: are there asymmetries in the progenitor AGB stars themselves, and what produces density contrast resulting in asymmetric circumstellar AGB envelopes?

Recent results at optical, infrared, and radio wavelengths are beginning to shed light on the question of asymmetries in progenitor AGB stars. The non-spherical nature of o Ceti is well known and has been observed with HST (Karovska et al. 1997). Infrared-interferometry observations of circumstellar dust shells have also shown evidence for non-spherical envelopes in fits to the visibilities. Circumstellar maser emission, especially SiO maser emission, may provide the best tracer for asymmetry in progenitor LPVs. The SiO masers lie inside the dust formation point in the upper atmosphere of the star at distances of 2-5 stellar radii (10’s of AU). The fact that asymmetry in the circumstellar envelope is evident even at the close distances sampled by the SiO masers has been observed most recently in the supergiant NML Cygni (Figure 2**;** Boboltz & Marvel 2000).

Hypotheses for producing asymmetries in PNe include non-radial pulsations in AGB stars, or the possibility of unseen companions (Groenewegen 1996). There is little observational evidence to verify either of these scenarios since the tools to do such a study are limited. SIM observations of selected AGB stars will provide the observational evidence necessary to distinguish between the two competing models. The presence of a binary companion or non-radial pulsations should have distinctly different signatures in the variation of the astrometric position of the star, and any wander should be easily detectable with SIM. For example, Soker (1998) describes the scenario necessary for the evolution of a massive AGB in a binary to a bipolar PNe. In this scenario, the mass of the secondary must be $M_2 \geq 0.1\ M_\mathrm{M}$ and the separation when the primary enters the AGB phase should be in the range 1 AU P a P 10 AU. For a typical Mira mass of ~1.5 M_M at a distance of 500 pc, this translates to a reflex motion of ~100 B 1000 μas, which should be easily detected in the 10 μas observations we are proposing. We propose to observe a sample of Mira and semi-regular variables in which the SiO maser emission has been imaged prior to the launch of SIM. This will provide us with a number of stars in which the degree of asymmetry in the upper atmosphere of the star is known prior to SIM observations. We will then be able to correlate any wander in the SIM position with the direction of asymmetry in the upper atmosphere of the LPVs to look for any evidence of binary companions or non-radial pulsations.

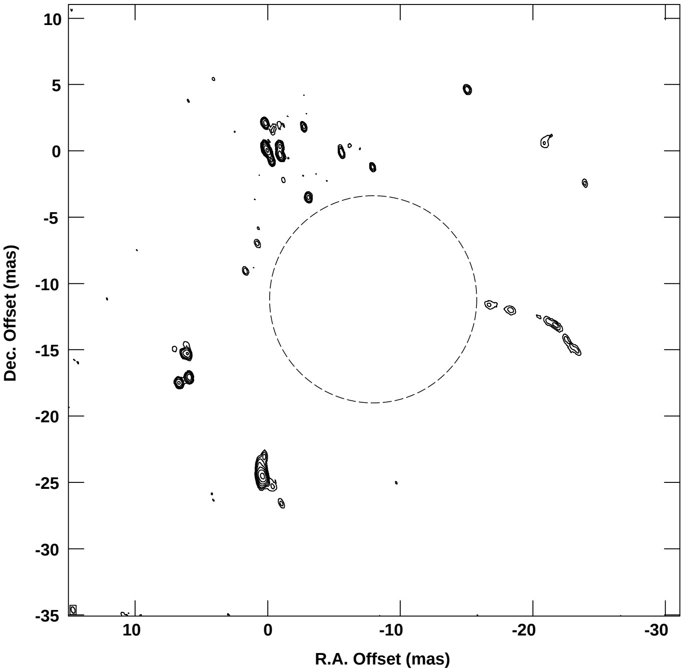

Figure 2 Total intensity VLBA image of the *v=1, J=1–0* 43-GHz SiO maser emission towards NML Cygni integrated over the LSR velocity range from –27.9 km s^{-1} to +13.7 km s^{-1}. The dashed circle represents a stellar disk with a diameter of 16 mas (32 AU) at the assumed distance of 2 kpc to NML Cygni. The position of the stellar disk relative to the SiO masers is also assumed.

2.5.2 Relative Maser/Optical Photocenter Positions

In Figure 2 above, the dashed line used to represent the stellar disk of the supergiant NML Cygni has a diameter which is estimated from the luminosity of the star. In addition, the position of the star relative to the SiO maser shell is unknown, and the placement of the dashed circle in the figure is purely conjectural. As Figure 2 demonstrates, the study of circumstellar maser emission suffers from the same limitations in the radio/optical link as do the study of quasars and radio stars. Knowledge of the true position of the star would greatly enhance the quality of the physics that can be done using circumstellar masers including: maser pumping mechanisms, velocity structure, polarization, and proper motion studies. As an example, in SiO maser proper motion studies, different epochs of observations are registered to one another via one or more maser features on the edge of the tangentially amplified maser shell (Boboltz, Diamond & Kemball 1997; Diamond & Kemball 1998). The errors in the relative positions of these masers are on the order of 10 μas. Knowledge of the stellar position would allow the registration of the maser positions to the true stellar position on the microarcsecond level, thus eliminating the inherent bias in current methods of maser position registration.

2.5.3 Linear Scale Sizes for Circumstellar Envelopes

In addition to measuring the position of the optical photocenter with respect to the circumstellar maser positions, SIM will be able to accurately establish the linear scale sizes for the various maser and dust regions of the circumstellar envelopes by determining the distance to these long-period variables via accurate parallax measurements. Knowledge of these scale lengths is important in theories relating to the chemistry of circumstellar envelopes, the formation points of circumstellar masers and dust shells, the strength of the stellar magnetic field at various distances from the stars as measured by SiO and OH maser polarization observations, and the linear velocity of circumstellar gas as traced by maser proper-motion studies.

2.5.4 Calibration of the Mira Distance Indicator

As in other types of variable stars, Mira variables show a well-studied relationship between the period and luminosity of the star. This relationship is important since it indicates that Mira variables can be used as standard candles for galactic and extragalactic distances similar to Cepheid variables. Feast et al. (1989; 1996) established an infrared period-luminosity relationship for Mira variables in the LMC given by:

$$M_K = -3.47 \log P + 0.91.$$

This relationship was tested using Hipparcos parallaxes for 16 of the closest Mira variables (van Leeuwen et al. 1997) and for 18 close semi-regular variables (Bedding & Zijlstra 1998). Both studies found that the distances from the LMC period-luminosity relationship agree with the Hipparcos distances to within the errors in the Hipparcos parallaxes. Unfortunately, the Hipparcos parallaxes for the semi-regular and Mira variables used in the two studies are only good to about 20%.

A byproduct of the proposed SIM observations of a number of Mira and semi-regular variables with maser emission will be an accurate calibration of the Mira period-luminosity relationship. Through the proposed parallax measurements, SIM will be able to calibrate the Mira distance scale to better than 1 percent. Since the SIM 10 mas resolution will limit our observations to distances greater than 200 pc, these observations should compliment the Hipparcos studies, and should help to establish an accurate zero-point for the Mira variable distance scale.

3 Preparatory Work to Enable Key Science Objectives

3.1 Importance of SIM/ICRF Frame Tie

The International Celestial Reference Frame (ICRF) is a quasi-inertial reference frame based upon a database derived from over 20 years of Very Long Baseline Interferometry (VLBI) observations of extragalactic objects (Ma et al. 1998) and is the realization of the International Celestial Reference System (ICRS) (Arias et al. 1995) at radio wavelengths. The ICRF has been adopted by the International Astronomical Union (IAU) as the fundamental celestial reference frame, replacing the FK5 optical frame on 1 January 1998.

The unprecedented astrometric accuracy and brightness sensitivity of SIM will allow, for the first time, a direct connection between the stellar and extragalactic frames. A direct and accurate link between the ICRF and SIM frames will allow many scientifically interesting comparisons between multi-wavelength observations of specific objects, and comparisons between SIM catalogs and objects in catalogs made with other instruments. The accuracy of the SIM frame will surpass the accuracy of the ICRF by an order of magnitude or more. Consequently, SIM may quite possibly define the next generation ICRF. However, the radio reference frame (current ICRF) will remain relevant for many years in the areas of geodesy and radio astronomy, disciplines that rely heavily on the technique of radio interferometry.

SIM expects to use an all-sky astrometric grid, consisting of several thousand stars, for astrometric instrumental calibration and to perform wide-angle (or global) astrometry. To the extent that SIM is an astrometric mission, the all-sky astrometric grid is the cornerstone of mission operations. Among the reference objects, SIM has plans to observe numerous extragalactic objects (nominally quasars) to establish a quasi-inertial anchor for the all-sky astrometric grid. Although these extragalactic sources need not be radio-loud, use of suitable radio-loud (ICRF) quasars for this purpose (in addition to providing a link to the ICRF) will minimize SIM calibration overhead.

To enable a high precision tie between the ICRF and SIM frames, candidate quasars must necessarily exhibit a high degree of astrometric stability at both radio and optical wavelengths. It is well known that source structure at radio wavelengths has a significant impact on (degrades) positional accuracy (Fey & Charlot 1997, 2000). Currently, the ICRF will limit the accuracy of a SIM/ICRF frame tie if the projected accuracies for SIM are realized (Fey et al. 2000). Additionally, there is very little available information on whether the optical 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 μas at 1 Gpc), some degree of photocenter wandering 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.

As a necessary and fundamental part of this Key Science proposal, we propose a program of ground-based radio and ground and space-based optical observations targeting candidate radio/optical link sources. The goal of this program is to determine the ultimate accuracy to which radio and optical astrometric observations can be made, thus enabling the most accurate SIM/ICRF link feasible. This will allow the precise overlay of the radio and optical emission structures associated with the science targets of this Key Science proposal. Additionally, the proposed work will provide the SIM project an improved list of high astrometric quality ICRF quasars suitable for anchoring the SIM astrometric grid and for tying the SIM reference frame to the ICRF/ICRS with the highest possible precision. Our previous work (under NRA 98-OSS-07) has produced a list of candidate ICRF quasars for use by SIM, but formation of this list required a number of compromises; particularly in terms of radio astrometric quality of the sources. We are led to the conclusion that additional radio and optical observations are required.

We will also investigate the feasibility of using other morphological classes of extragalactic radio sources as reference frame objects. The compact, symmetric objects (CSOs) for example, have complex structure, but still have prominent, easily identified, nuclear components (e.g. Taylor et al. 1996). Most current ICRF sources are core dominated and many have superluminal jets. The emission from these core-jet radio sources is probably beamed towards us, with concomitant amplification of geometric effects. The CSOs, on the other hand, may well be viewed more nearly side-on. With adequate structure modeling, it may be possible to use these sources as accurate fiducial points. Another candidate morphological class of sources would be the Intra-Day Variability (IDV) sources. These sources show strong flux density variations (up to about 50%) on timescales of one day or longer. The most likely interpretation for this IDV is scintillation in the Interstellar Medium, implying microarcsecond source angular sizes at centimeter wavelengths.

3.2 Preparatory Quasar Observations

3.2.1 Quasar Radio Observations

As part of worked performed under NRA 98-OSS-07 (W-19, 688) and based on astrometric and imaging VLBI data taken through May 1999, we developed a new set of stringent criteria for selecting high radio astrometric quality sources and provided a filtered list of ICRF sources to the SIM project (see Fey et al. 2000). We identified two notable “problem” areas with respect to SIM. The first is a serious lack of high radio astrometric quality sources in the Southern Hemisphere. This cannot be attributed to any intrinsic property of Southern ICRF sources, but instead the astrometric quality of Southern Hemisphere sources is severely limited due to sparse and infrequent observation. The second notable result from our previous work is that many of the ICRF sources with the highest astrometric quality in both the Northern and Southern Hemispheres are optically quite faint.

The accuracy of astrometric VLBI is currently limited to about 0.2-0.3 mas mostly by tropospheric propagation effects and by the apparent motions of the sources due to variable intrinsic structure (Ma et al. 1998). Consequently, the ICRF will limit the accuracy of a SIM/ICRF frame tie. To get a rough estimate of the accuracy of the frame tie, we performed a Monte-Carlo simulation using the filtered list of ICRF sources provided to the SIM project by Fey et al. (2000). First we assume that the position uncertainties from SIM are negligible compared to the ICRF position uncertainties and that the ICRF position uncertainties represent random errors drawn from a Gaussian distribution. Position offsets for individual sources are generated using a random number generator with zero mean and unit variance. The three orientation angles are then solved for in an unweighted least-squares solution. The mean of the calculated angles are expected to be zero; the scatter about the mean angles gives an estimate of the expected accuracy. The results over many realizations show that, if the projected astrometric accuracies for SIM are realized, the SIM/ICRF frame tie will be limited to about 110 μas. If the radio and optical emission from the science targets of this Key Science proposal are to be successfully overlaid at the level required (nominally less than 100 μas), then additional radio observations are necessary to overcome the limitations of the radio frame.

To facilitate an accurate SIM/ICRF frame tie, therefore enabling the science objectives of this Key Science proposal, we intend to undertake a dedicated VLBI observing program targeting the infrequently observed optically brighter Northern and Southern Hemisphere ICRF quasars with the goal of significantly improving their radio astrometric quality. Previous VLBI astrometric observing programs have not selected targets based on optical brightness. In support of the science objectives in this Key Science proposal, we will begin a dedicated observing program to investigate and assess the radio astrometric properties of the optically brighter sources. For example, increasing the astrometric position uncertainty to 0.3 mas for those sources in the candidate ICRF frame tie list of Fey et al. (2000) that have position uncertainty greater than 0.3 mas, increases the estimated frame tie accuracy to about 50 μas.

In addition to standard astrometric VLBI observations, imaging observations will also be undertaken, with particular emphasis on imaging sources in the Southern Hemisphere. The vast majority of Southern Hemisphere ICRF sources have never been imaged; Fey & Charlot (1997, 2000) have shown that source structure is an important aspect for assessing astrometric position accuracy and stability. Statistically significant wander of the astrometric VLBI positions of quasars is usually attributed (e.g. Fey et al. 1997) to intrinsic changes in source structure. As part of the maintenance of the ICRF, we have begun a research program to correct for temporal wander of astrometric VLBI quasar positions through inclusion of astrophysically reasonable source structure models (e.g. core-jets). We propose to continue research into the modeling of source structure effects and their impact on astrometric position history. Source structure correction models will not only prove crucial for precise alignment of individual sources in the global ICRF and SIM astrometric frames, but modeling research also may have a significant positive impact on the amount of SIM calibration time spent observing extragalactic sources. If current modeling research proves effective in providing astrometric correction for source structure then it may be possible to achieve a precise link between the ICRF and SIM frames using brighter quasars previously rejected due to structure effects, resulting in considerable savings in SIM calibration time.

Through this proposed program of observation and analysis, we expect that the radio astrometric quality of some fraction of the optically brighter ICRF quasars will be improved to the point that they will be useful to the SIM program, replacing fainter quasars on the SIM list of candidate link objects; making a significant reduction in the SIM mission calibration overhead.

3.2.2 Quasar Optical Observations

Knowledge of the optical emission structure of the sources comprising the candidate list of SIM/ICRF link objects is of critical importance. Aside from optical brightness and redshift, little is known about the optical properties of ICRF sources. Optical positions on the 50 mas level in the Hipparcos system have been obtained for 327 ICRF sources by Zacharias et al. (1999). The radio and optical centers of emission of this sample coincide at about the level of their positional uncertainty suggesting that, on average, there are little or no optical structure problems (at least at that level). However, the spatial resolution of this survey varied between 0.40 and 0.68 arcseconds. The radio/optical position offsets are therefore not a robust indicator of optical emission structure on scales smaller than about 0.5 arcseconds. Maoz et al. (1993 and references therein) searched a total of 498 quasars (with redshift greater than one) for evidence of gravitational lensing using the 0.043-arcsecond resolution Planetary Camera of the Hubble Space Telescope. Only one lensed candidate source was found. The remaining objects showed no evidence of point sources at separations smaller than about 2-3 arcseconds from the target quasar. Their simulations showed that multiple images with brightness ratios of up to several magnitudes would have been detected, down to image separations of approximately 0.1 arcseconds. Only about 30 of the 498 sources surveyed by Maoz et al. (1993) are ICRF sources.

In support of SIM and the science objectives of this Key Science proposal, we intend to begin a ground and space-based optical observing program targeting SIM candidate quasars. Additional high-resolution optical observations are required to assess the optical astrometric quality of ICRF sources. We intend to propose for direct high-resolution imaging observations of the SIM candidate quasar lists with the Hubble Space Telescope to extend the snapshot survey of Maoz et al. (1993) to the ICRF.

Motion of a quasar's photocenter may result from a variable nucleus in combination with effects in the larger (albeit fainter) host galaxy. Using existing USNO optical observing programs we will obtain optical astrometric positions of SIM candidate quasars, comparing the positions of the optical and radio counterparts of individual sources. Offsets between optical and radio astrometric positions for specific SIM candidate quasars in excess of the standard errors may be an indication of structure effects.

Additionally, the USNO 61 inch astrometric telescope in Flagstaff, AZ will be used to search for differential position wander between quasars within the same FOV. Differential positions can be measured to about several hundred microarcseconds with this telescope. The eventual goal of this line of research is to gain insight into the optical astrometric quality of the SIM candidate quasars, eventually including optical astrometric quality as an additional criterion for selecting the optimum SIM/ICRF link objects.

3.3 Radio Star Preparatory Science

3.3.1 Stellar Radio Continuum Observations

Although there are nearly 1000 stars that have been detected at least once at centimeter wavelengths (Helfand et al. 1999), stellar VLBI observations have been primarily limited to a few well-studied sources. New unbiased searches for radio stars (Condon et al. 1997; Helfand et al. 1999) from large-scale surveys such as the NRAO VLA Sky Survey (NVSS) and the Faint Images of the Radio Sky at Twenty-cm (FIRST) have added to this total, including new sources strong enough to be observable using VLBI techniques. In preparation for SIM and this Key Science Proposal, we have begun a program of VLBI radio-star observations of 8 strong stellar radio emitters. In addition to current and future VLBI observations, in the upcoming VLA proposal cycle we will submit a proposal to use the VLA in conjunction with the Pietown VLBA antenna (VLA-PT link) to observe a sample of about 100 radio stars. The VLA-PT link offers the added sensitivity of the VLA over the VLBA along with a factor of 2 resolution over the VLA in A configuration.

3.3.2 NPOI Observations of Radio Stars

In addition to observations of the radio continuum emission of chromospherically active stars, we plan to begin observations of the optically bright binaries in the group using the NPOI. Observations with the NPOI will allow us to accurately determine the orbital parameters for these objects along with stellar radii and magnitudes of the binary components. By combining radio, SIM, and NPOI observations, we should be able to precisely determine the location of the radio emission relative to the two stars in the binary.

3.3.3 Circumstellar Maser Observations

Circumstellar maser observations in coordination with SIM observations of the optical photocenter of Mira and semi-regular variables may provide a crucial key to understanding the evolution of asymptotic giant branch stars to planetary nebulae. To date there are no large-scale imaging surveys of the maser emission towards these objects. In support of SIM and the AGB star science objectives of this Key Science proposal, we intend to begin a survey of 100 known AGB stars with SiO maser emission. Beginning with the June 1, 2000 proposal cycle, we will propose for time on the VLA–PT link to image the 100 chosen sources. This new configuration will make such a large-scale imaging survey possible by adding the sensitivity of the VLA to the resolution provided by the Pietown VLBA antenna. These images will provide the necessary information on asymmetries in the upper atmosphere of AGB stars to be used in conjunction with SIM measurements of the position, proper motion, parallax, and photocenter wander of these objects.

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