Executive Summary

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

Category: Key Project
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We propose to use the unique capabilities of SIM to answer three key questions about active galactic nuclei (AGN) and, in doing so, demonstrate in the first year of SIM operation how well the optical and radio reference frames can be linked. We request 3% of SIM observing time for this Key Project.

1. Do the cores of galaxies harbor binary supermassive black holes remaining from galaxy mergers?
2. Does the most compact optical emission from an AGN come from an accretion disk or from a relativistic jet?
3. Does the separation of the radio core and optical photocenter of the quasars used for the reference frame tie change on the timescales of their photometric variability, or is the separation stable?

Questions 1 and 2 address the nature of the AGN phenomenon, and the production of relativistic jets in a fraction of these active galaxies. Active galaxies are a rich observational field, and much is known from emission line spectroscopy, polarization, and variability studies (such as reverberation mapping of nearby Seyferts). Models of blazar variability suggest that the intrinsic size-scales are very small (light days) in extent. Currently, the highest resolution available is with high-frequency VLBI imaging at ~ 100 microarcsec (μas) resolution, and the best optical images from HST have about 50 milliarcsec resolution. The potential discovery space for observations of AGN with SIM is therefore surprisingly broad, since SIM can detect photocenter shifts at the few μas level. A variety of AGN phenomena will be visible on such scales, including answers to questions 1 and 2.

With a 10-milliarcsec fringe spacing, SIM is not expected to resolve AGN at significant redshift (though the option of imaging at this resolution would represent a major observational piece of the AGN puzzle). This proposal seeks to exploit SIM's astrometric capability by measuring positions of moderately faint ($V = 15 - 18$) targets to an accuracy of ~ 10 μas)

Question 3 relates to the practical issue of tying the SIM reference frame (internally consistent at 4 μas) with the International Celestial Reference Frame, which is the adopted IAU standard for all observations. We do not propose to perform the frame tie itself, as

this is a responsibility of the SIM Project. Instead, we will show, within about the first year, whether the frame tie will be limited by "astrophysical noise". If so, we would work with the Project to improve the selection and observation of suitable reference objects.

These first steps in microarcsecond astrometry of quasars should focus on understanding of a small number of objects, selected on the basis of known properties, so that the results may by simply interpreted. Some of the nearest and best-studied archetypal quasars and AGN are M 87, 3C 273, 3C 279, and 3C 345, for which detailed VLBI imaging is available. OJ 287 is believed to have the best case for periodicity which might indicate binary black holes. We do not attempt a statistical study, which would be well beyond the scope of SIM. The richness of AGN phenomena requires samples of hundreds or more objects to separate out different physical effects.

We will perform the following specific observations to answer these questions.

1. Measure the separation between archetypal core-jet AGN, quasars selected for their compactness from the radio sources that define the extragalactic reference frame, and reference stars in four "target-rich" tiles, e.g., a 15-degree field of regard containing both 3C 273 and M 87.

2. Use multicolor, differential phase techniques to measure the size and stability of the optical continuum emission which will tell us how the optical photocenter location depends on wavelength.

3. Determine quasar positions within a tile to 20 μas in the first year, using monthly observations. The precision within the tile is independent of the full mission Grid Star reference frame. Significant early science results, and validation of the optical-radio frame tie, can be obtained during the first year of SIM operations.

1 Introduction

Some of the most puzzling questions in astronomy today involve the origin and structure of radio-loud quasars. A favored theory involves the activation of relativistic jets from the fueling of a supermassive black hole through an accretion disk; conditions appear to be briefly favorable after two galaxies collide and merge.

Figure 1 shows an artist's depiction of the observed features of an active galactic nucleus (figure courtesy of C.M. Urry and P. Padovani). The outer clouds (shaded gray) produce the narrow emission lines. The inner clouds (shaded black) produce the broad emission lines. In some AGN an outer optically thick, "dusty torus" is seen orbiting the black hole system. This torus is probably related to an inner accretion disk- black hole system which is the actual powerhouse of the AGN. In radio-loud AGN two oppositely-directed radio jets are ejected perpendicular to the torus/disk system.

Although there is a wealth of observational data on AGN, several very basic questions have not been answered definitively. We propose SIM observations which address, and should answer, three key questions about AGN. This project is well-suited to early-release science results, and also to demonstrate in the first year how good the SIM and ICRF (International Celestial Reference Frame) radio reference frames can be linked. We will need about 3% of SIM observing time to accomplish these goals.

Our three questions are posed as follows:

1. Do the cores of galaxies harbor binary supermassive black holes remaining from galaxy mergers?

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

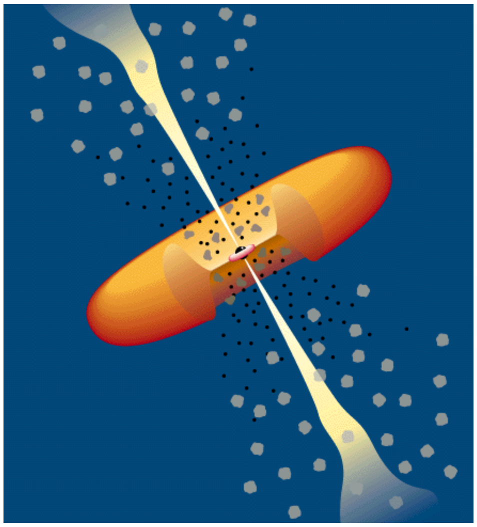

Figure 1: The inner regions of an active galaxy, including the outer torus, the accretion disk, the jets, broad- and narrow-line clouds (copyright PASP and reprinted with permission of the authors).

3. Does the separation of the radio core and optical photocenter of the quasars used for the reference frame tie change on the timescales of their photometric variability, or is the separation stable?

We have designed an observing program to address these questions. The observing program makes efficient use of SIM, and limits the impact of systematic errors in the computed astrometric positions of targets (Section 5), by relying primarily on observations within a SIM "tile". The specific observations can be summarized as follows:

1. We will measure the angular separation between (a) archetypal core-jet AGN, (b) quasars selected for their compactness from the radio sources that define the extragalactic reference frame, and (c) reference stars in four "target-rich" tiles, *e.g.*, , a 15-degree field of regard containing 3C 273 and M87. Comparison of the optical angular separation between archetypal AGN and extragalactic reference frame quasars with the radio angular separation measured with VLBI, as a function of time, directly addresses the question of the radio-optical frame tie.
2. We will use multicolor differential phase techniques to measure the size and stability of the optical continuum emission which will tell us how the optical photocenter location depends on wavelength.
3. We will determine quasar positions within a tile to 20 μas within one year, using monthly observations. The precision within the tile is independent of the full mission Grid Star Reference Frame. Significant early science results, and validation of the optical-radio frame tie, can be obtained during the first year of SIM operations.

In the following sections, we address each question in turn, and our method for answering it. We then describe our SIM Observing Plan and our Preparatory Science Plan. We present a list of our milestones before and after launch, covering eleven years. Throughout the proposal, we use $H_o = 75$ km/s/Mpc and $q_o = 0.5$. At the assumed 15-Mpc distance of M87, 10 μas $= 6.8 \times 10^{-4}$ pc; for a quasar at moderate redshift, such as 3C 345 at $z = 0.595$, 10 μas $= 0.05$ pc.

2 Science Program

2.1 Finding Binary Black Holes With SIM

Do the cores of galaxies harbor binary supermassive black holes remaining from galaxy mergers? This is a question of central importance to understanding the onset and evolution of non-thermal activity in galactic nuclei. If massive binary black holes are found, we will have a new means of directly measuring their masses and estimating the coalescence lifetimes of the binaries.

An entire AGN black hole system may be in orbit about another similar system (Figure 2). Such a situation can occur near the end of a galactic merger, when the two galactic nuclei themselves merge. Time scales for the nuclei to merge, and the black holes to form a binary, are fairly short compared to the Hubble time: of order the galaxy merger time

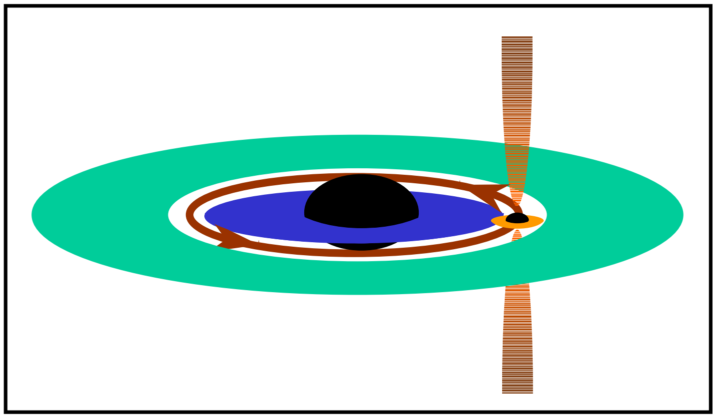

Figure 2: Schematic diagram of a possible binary black hole system. Such a system could have a number of different configurations. The emission could be tied to either the central hole or its companion.

(a few hundred million years). The binary phase can last a similar amount of time until the separation is well below one parsec, at which time gravitational radiation losses cause it to coalesce more rapidly. The gravitational radiation lifetime is about 3×10^6 yr (Krolik 1999). The frequency of occurrence of such objects in the general quasar population is small, hence, we will select the best candidates (such as OJ 287; see Kidger [2000]) for SIM detection of binary black holes during our pre-launch Preparatory Science Program.

For example, a binary black hole system with a period of 24 years (the period of the binary black hole in OJ 287: the observed photometric periodicity is half the orbital period as the secondary dips in and out of the primary's accretion disk) and a mass of 10^9 solar masses has a separation of 0.036 pc. At the distance of OJ 287 (765 Mpc), this separation subtends 11 μas, and the orbital motion expected during a five-year span is about 14 μas. This is comparable to the 13.2 μas 1-D single measurement accuracy relative to the tile reference frame (see Table 2) for a R=17.5 mag AGN, and compares to the full mission accuracy of 5.6 μas.

OJ287 is one of the most promising candidate sources for a binary black hole, based on evidence of a long-term periodicity in its level of activity. However, any AGN could harbor a binary black hole; it is not clear that a periodic variation in radio or optical brightness would necessarily be produced in most cases. Thus, our ability to test for binary black holes in relatively nearby AGN is at least as important as testing this hypothesis for OJ287 in particular. For OJ287 our observations will be sensitive only to very massive black hole binaries. However, for closer systems (3C273, M87) we will be sensitive to much lower mass binaries.

We can detect binary black holes by measuring optical position changes due to orbital motion, just as SIM can detect periodic shifts in the photocenters of stars caused by much smaller orbiting planets. This is the "astrometric reflex motion" signature. The very best AGN to examine for binary black holes in their cores are those whose optical light is completely dominated by beamed emission from the relativistic jet rather than thermal emission from the accretion disk. Thus, we select those objects whose jets are pointed right at us. These are, of course, the blazar class we have been studying for many years, and which make up the vast majority of the International Celestial Reference Frame (ICRF) sources (see, for example, Unwin *et al.* 1994, Wehrle *et al.* 1998, Piner & Kingham 1998). The reason for this is that beamed jet emission is expected to be associated with an individual black hole in a binary system, while thermal disk emission may come from a region surrounding both black holes (a "shared" accretion disk whose scale is larger than the black hole separation). If an object's jet is pointed away from us, its optical emission may be dominated by the Big Blue Bump of the accretion disk rather than by the non-thermal power-law emission. For this type of object, we cannot distinguish the motion of a hot spot in the accretion disk from the motion of emission from primary, secondary, or both black holes without using the color-dependent differential phase measurements we describe below.

In summary, the test for binary black holes is to observe the motion of the photocenter of a blazar over the course of the SIM mission: a binary will trace an elliptical path; if the detected motion is random, then the blazar shows no evidence of binarity.

2.2 The Location of the Most Compact Optical Emission

Does the most compact optical emission from an AGN come from an accretion disk or from a relativistic jet? In this section, we first describe the overall structure of AGN: the accretion disk and hot corona or wind, and then the relativistic jet. Second, we outline what SIM should see depending on which components are dominant. Our robust observing technique is describe under the Section on our SIM Observing Plan.

2.2.1 The Accretion Disk and Hot Corona or Wind Components

Thermal emission. Our knowledge of the inner accretion disk system comes mainly from theoretical models; one of the more popular ones is depicted in Figure 3. The disk itself contains at least two possible regions that produce optical continuum emission. When the accretion rate is high (near the Eddington limit, as is suspected in quasars, Seyfert galaxies, and broad-line radio galaxies), the disk is expected to be optically thick to free-free absorption. This produces a thermal peak in the near ultraviolet region, which is believed to be the "Big Blue Bump" seen in optical-UV quasar spectra (Band & Malkan 1989; Zheng *et al.* 1995). For a typical $10^9\,M_\odot$ black hole system, accreting at 10% of the Eddington rate, the diameter of the portion of the disk that is radiating at a temperature of $10^4\,K$ or above is $\sim 3.6 \times 10^{16}$ cm, or 0.012 pc. (See, for example, models by Shakura & Sunyaev 1973.) At the nearby distance of 15 Mpc, this region would subtend an angular size of $\sim 160\,\mu$as, while at a redshift of 0.5 ($D \sim 1\,$Gpc), the angular size would be only $\sim 2\,\mu$as.

Non-thermal emission. The Big Blue Bump, however, does not appear to be the dominant source of photo-ionizing radiation in quasars. The main source of optical emission seems to be a steep power-law source extending from the infrared to well shortward of the Lyman limit in the ultraviolet. (Such a hard spectrum is necessary in order to produce emission lines of the high-ionization species of carbon silicon, nitrogen and oxygen, for example Osterbrock & Matthews [1986]). This emission therefore is probably non-thermal either optical synchrotron or Compton-scattered emission from a radio or sub-millimeter

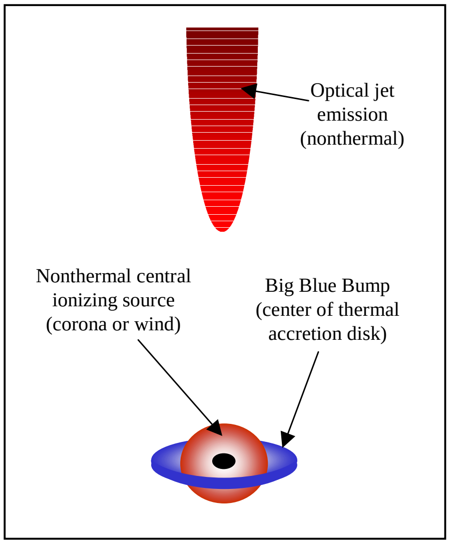

Figure 3: Schematic model of the central ionizing source (after Band & Malkan 1989) and jet (after Königl 1981) for a typical AGN. Size of the central disk/corona structure is $70-120\,\mathrm{R_{Sch}}$ ($100-160\,\mu$as for M87, or only $1-2\,\mu$as for a typical quasar at a redshift of 0.5). *The offset between the optical jet and disk emission for 3C 345 ($z = 0.595$) is expected to be of order* $0.4\,$pc *or* $\sim 80\,\mu$as.

source. While there is not yet a complete consensus on where this emission originates in the black hole system, for most quasars it is very *un*likely that this nonthermal ionizing source is beamed optical radiation from a relativistic jet. The reason for this is that models of the broad emission line region do not indicate that it subtends a very narrow cone; indeed, some quasars' broad line regions fit a Keplerian *disk* profile very well (Eracleous & Halpern 1994). The nonthermal ionizing source, therefore, emits fairly isotropically. One possible model for this central source is a magnetized corona or wind emanating from the central region of the accretion disk, which would emit optical/infrared synchrotron as well as thermal and Comptonized X-rays. Models of this region (*e.g.*, Band & Malkan 1989) indicate a size of only ~ 70 Schwarzschild radii. At a redshift of $z = 0.5$, this subtends an angular size of only $\sim 1\mu$as, centered on the black hole.

In summary, for AGN in which the disk emission dominates (radio loud AGN viewed at a large angle to the jet axis), we expect the red portion of the spectrum (dominated by the nonthermal ionizing source) to be spatially coincident with the blue portion (dominated by the thermal disk emission), as both emission regions are physically centered on the black hole. Any color-dependent position shift in such objects seen with SIM observations would challenge the current models of accreting systems in AGN.

2.2.2 The Beamed Relativistic Jet

About 10% of AGN possess a powerful relativistic jet. This jet appears to be ejected in a direction approximately perpendicular to the accretion disk (Figures 1 and 3). The process of acceleration and collimation of jets appears to take place near the central regions of a magnetized accretion disk, with centrifugal and magnetic pressure forces driving the outflow and magnetic pinch forces effecting the collimation. However, as the rate of occurrence of powerful jets in AGN is small, additional factors are believed to be important. In particular, it has been proposed that a powerful jet cannot be produced unless the central black hole is spinning rapidly (Wilson & Colbert 1995; Blandford 1999; Meier 1999).

If an AGN is radio-loud, *and* viewed at a small angle to the jet axis (a "blazar"), then there is a third possible compact source of optical continuum emission in the system which would be detectable by SIM: emission from the relativistic jet beamed toward the observer. The radio emission in such objects is also very compact. The Königl model for relativistic jets (Königl 1981) predicts that, in the optical, the majority of the emission comes not from synchrotron emission from the central portion of the jet but rather from synchro-self-Compton emission in the region of the jet where the synchrotron emission peaks in the radio or millimeter (Hutter & Mufson 1986). A detailed application of this model to 3C 345 ($z = 0.595$), for example, predicts the optical emission to lie $\sim 80\,\mu$as from the other two above emission regions (*i.e.*, from the black hole) nearly coincident with the 22 GHz radio emission ($\sim 70\,\mu$as or 0.4 pc from the black hole). *SIM can test the Königl model predictions directly.*

2.2.3 Distinguishing AGN Models using Color-Dependent Astrometry

We propose to use SIM's ability to precisely determine changes in position between red and blue light from a single source to test two general models for the optical structure of AGN, as outlined above:

Model 1 Most of the red light is power-law synchrotron emission along the relativistic jet.

Model 2 Red light comes from synchrotron or inverse Compton emission from a hot, magnetized corona or wind above the accretion disk.

In both models, most of the blue light is thermal emission from the optically thick part of the accretion disk the source of the "Big Blue Bump" in many quasars and AGN. The discriminator between these is is very simple: is there an offset between red and blue photocenters? See Figure 3 for a sketch of the AGN emission regions on the size scale relevant for SIM. The models have the following observational consequences:

In Model 1, red light comes from the jet, so its photocenter will be offset (along the position angle of the jet) from the blue photocenter associated with the accretion disk. In Model 2, red light comes from a disk corona or wind, so the red and blue photocenters should be coincident.

We can measure the offset between red and blue photocenters, and monitor any changes in the separation, by measuring the phase shift of the white light fringe between the red and blue halves of the SIM detector (Section 5.5). This is a differential measurement, and is largely independent of the absolute delay accuracy or precise knowledge of baseline orientation, and depends only on the available SNR of the detected fringes. In addition, by repeating the tile observations during the mission, we can learn whether this location is stable over time.

Examples of What SIM Should See in Specific Targets

M87: In this nearby radio galaxy, we expect the optical emission to be dominated by the accretion disk region because its jets are not pointing within a few degrees to our line of sight. We therefore expect relatively large offsets between the optical photocenter and radio photocenter (which is dominated by emission from the optically thick base of the radio jet). As noted below, this shift is expected to be on the order of 100μas for 3C 345, and should be even larger for this low-redshift radio galaxy where the angular-linear scale is larger and the radio jets are not seen in projection.

3C 345 and MKN 501: In 3C 345 (Unwin *et al.* 1994), optical jet emission should be roughly coincident with the 22 GHz radio emission, at about 80μas from the black hole. Color-dependent position shifts may be observable across the SIM band analogous to the frequency-dependent separation effect well-known in VLBI observations (the Königl model predicts a shift of 30 μas from the red to the blue end of the SIM band for 3C 345). In the TeV blazar MKN 501, the maximum synchrotron turnover frequency does not occur until the optical band or higher. in this case we expect the optical synchrotron emission to come from the base of the jet very close to the black hole and well-separated from the radio emission further out.

2.3 The Radio-Optical Frame Tie

Does the separation of the radio core and optical photocenter of the quasars used for the reference frame tie change on the timescales of their photometric variability, or is the separation stable? The radio sources used in the International Celestial Reference Frame are the most compact sources known. The most compact, flat-spectrum sources are also usually the most variable at radio and optical wavelengths. Radio flux variability is correlated with changes in structure on milliarcsecond scales, as we know from studying superluminal sources with VLBI. We observe optical jets in at least two of our target sources (M87; Figure 4 and 3C273), yet we do not have any optical images with resolution comparable to VLBI. Perlman *et al. 1999* have shown how polarized optical and radio features in M87 ("knots") on fraction-of-an-arcsecond scales (using Hubble Telescope and NRAO VLA data) are correlated. We therefore think there is a significant possibility that the ICRF quasars may show shifts in their optical centroids; observed optical photometric variability has timescales of minutes to months. While Wehrle and Unwin (in our capacity as SIM Project personnel) intend to collaborate with our colleagues (*e.g.*, , at JPL and USNO) to identify the optimal ICRF quasars for the frame tie, we are fully aware that it will not be possible to *guarantee* that the objects are unresolved on the important SIM angular scales. FAME should help, but its limited sensitivity will only permit observations of the half-dozen or so quasars which happen to be brighter than 15th magnitude during the FAME mission. A summary of the frame tie requirements is given in Section 6.13 of the SIMSWG Final Report; the proper motion accuracy goal and recommendation levels are 5 $\mu\text{as}\,\text{yr}^{-1}$ for 17th magnitude objects. The topics most affected by the accuracy of the reference frame tie are Galactic structure and extragalactic rotational parallaxes.

By devoting intense, early study to the nearest quasar and to archetypal quasars, as well as those believed to be oriented directly towards us (the $\gamma-$ray quasars), in the first year of the SIM mission, we should get a solid handle on the extent to which the optical photocenters are (a) well-defined (b) compact and (c) moving or stationary. The nearest

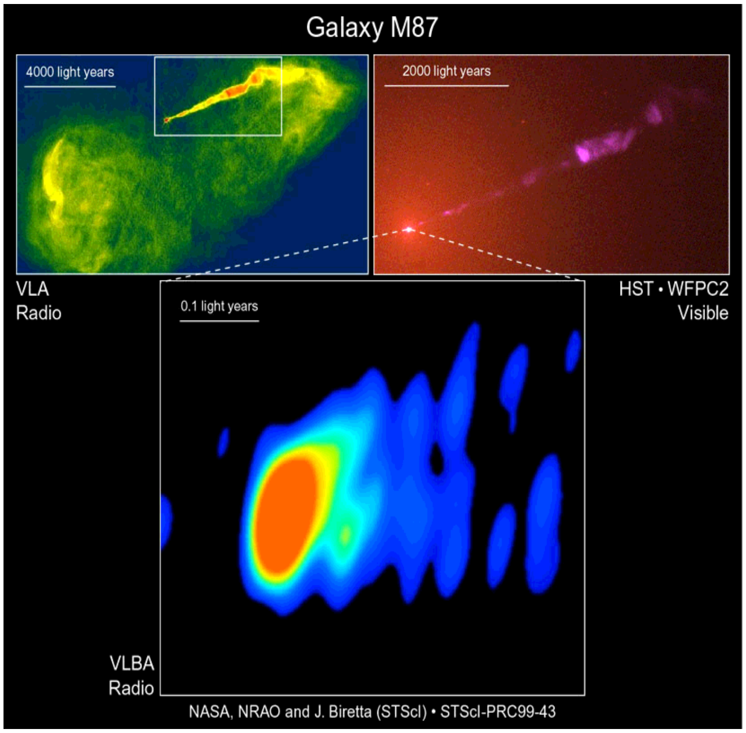

Figure 4: Mosaic of optical and radio images of M87. Image from Junor, Biretta and Livio 1999, reproduced with permission.

quasar, 3C 273, will certainly not be a frame tie object, but its proximity allows us to study variability with minimal effects of time-dilation. We will measure the angular separation between our scientifically interesting quasars and our ICRF quasars with both SIM and ground-based VLBI, and directly compare the radio and optical separations. We will have to do some VLBI during the SIM mission because the radio photocenter is usually a blurred combination of the core and first bright feature in the parsec-scale radio jet (eg., 3C 345, 3C 279) at high radio frequencies.

3 Preparatory Science

3.1 Phase-referencing VLBA and USNO VLBI Observations; Astrometry of the Radio Cores

The quasi-inertial International Celestial Reference Frame, composed of 212 radio-loud quasars, became the fundamental standard of positions in 1997. The USNO is an originator and principal maintainer of the ICRF with an active program of VLBI observations. The SIM Project has the responsibility of tying the SIM grid star reference frame to the ICRF; we do not yet know how many quasars will be required for this fundamental task. One of us (Piner) used USNO VLBI data in his PhD thesis. Jones (in Lestrade *et al.* 1999) has been involved in extensive phase-referencing on radio stars in support of the Hipparcos optical-radio reference frame tie. Because the quasars' radio structures change on scales of months to years, we will do selected phase-referencing observations to measure separations starting before and continuing during the SIM mission (we estimate this effort at about 2-months' FTE per year). We do *not* propose to conduct extensive VLBI monitoring as we have done on 3C 345 and 3C 279 in the past (cf. Unwin *et al.* 1994 and Wehrle *et al.* 2000; both programs are completed).

3.2 Keck Interferometer

Before we observe quasars from a space-based interferometer, we can verify that they have no structure seen by ground-based interferometers in the infrared. Currently, no optical ground based interferometer has enough sensitivity to detect even the brightest (13th magnitude) quasar. The Keck Interferometer will be operational in a shared-risk mode in 2003, and provides the roughly the same fringe-spacing as SIM (ten milliarcseconds), albeit in the infrared. We can fit Gaussian models to Keck Interferometer fringe visibilities; we can get very useful data in only a couple of nights without waiting for the outriggers on the Kecks. Keck telescope time is available through the NASA Origins sponsorship, and one of us (Wehrle) is a member of the Interferometry Science Center which will support Keck Interferometer observers.

3.3 Simulations

The main interferometry algorithms on SIM are currently being developed under the auspices of the Science Planning Team led by Unwin. Meier is a principal author of the science algorithms and software currently in use ("SIM-SIM"). We plan to use the mature SIM-SIM software to test our observing strategy; it provides an ideal early test case because our "standalone science" does not require the Grid solution. This is an excellent synergistic use of SIM-SIM for both Project and Key Project science goals.

3.4 Optical Monitoring

Several sources on our preliminary target list (OJ 287, 3C 345, Mrk 501) are optically violent variables. The sources may vary by several magnitudes on timescales of weeks and months (Figure 5, courtesy of T. Balonek). Optical monitoring programs currently underway include the SARA Observatory at Kitt Peak, the University of Florida's Rosemary Hill Observatory, the Torino Astronomical Observatory in Italy, and the Foggy Bottom Observatory of Colgate University. Many other observatories take part in short intensive campaigns on individual sources (eg. those who participated in our multiwavelength campaign on 3C 279, Wehrle *et al.* 1998). This has provided an excellent outreach opportunity to college-age students as it requires only a 0.5-1 meter-class telescope to provide excellent photometric data on bright blazars.

We will arrange collaborations with existing monitoring programs to obtain optical variability data on our targets, starting during the next year and continuing through the SIM mission lifetime. We will perform some intensive monitoring to determine the shortest variability timescales (such as micro-variability on timescales of minutes) and monthly observations to track longer term changes to verify each source's continued viability as a

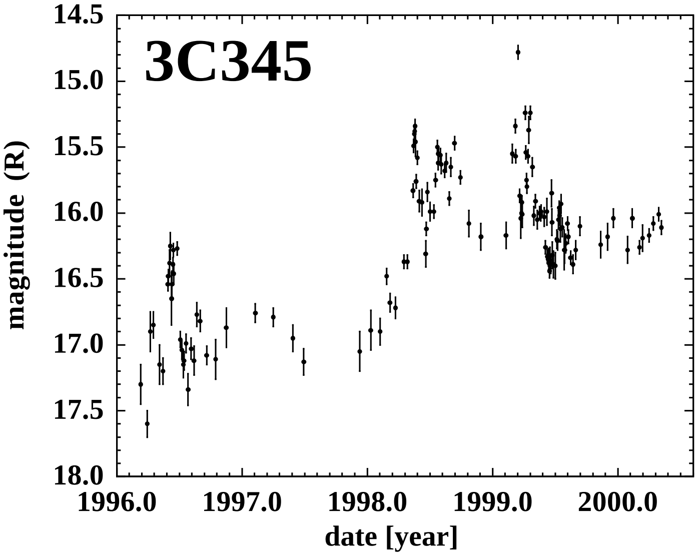

Figure 5: Optical light curve of 3C 345 showing two magnitudes of optical variability in the last four years, courtesy of T. Balonek.

SIM target. Ground-based monitoring contemporaneous with our SIM observations will also be important in case a blazar undergoes an optical flare.

4 Supporting Activities during the SIM Mission

We plan to hire a postdoctoral fellow during the year before SIM launch, and to have one postdoc on board during the five years of the mission. The postdoc will be a key person in formulating and checking the details of the science observing plan, in consultation with the PI and Co-I's, and of course, he or she will publish papers. We anticipate hiring a postdoc with experience in optical interferometry so he or she can "hit the floor running" when SIM starts generating data.

4.1 Continued Phase-referencing VLBA and USNO VLBI Observations; Astrometry of the Radio Cores

During the mission, we will conduct phase-referencing experiments with the VLBA and coordinate separate astrometric experiments with colleagues in the USNO group. The experiments will be identical in goals but optimized with the experience we will gain in our pre-launch observations. The radio experiments must be simultaneous with the SIM observations to ensure the best comparison of radio and optical angular separations in each tile; exactly how simultaneous is a question that we will need to understand before launch with the aid of our first exploratory phase-referencing experiments.

4.2 SIM Data Analysis

The SIM data analysis for our science observations is expected to be straightforward. Our measurement of the angular separations, and later reduction to the full Grid Star frame, is anticipated to involve standard software (Wehrle is a member of the ISC and Unwin is the head of the Science Planning Team). Standard data products from the ISC will be required, to be delivered to the PI and her team at JPL. Color-dependent phase-offset work is non-standard; it may be required by other teams in addition to ours. We will write the color-shift software and make it available to others.

4.3 Continued Optical Monitoring

We will continue coordinating our optical monitoring teams, concentrating on intensive monitoring for a few days around each of the four tile observations per month.

5 SIM Observing Plan

5.1 Science Target Selection

As we showed in Section 2, the potential discovery space for observations of AGN with SIM is surprisingly broad — almost nothing is known from direct imaging about active galaxies on scales less than $\sim 100\mu$as, and then only in the radio. Most of what is known about the (optically-emitting) inner regions of AGN comes from optical variability studies (such as reverberation mapping of nearby Seyferts) of the Broad Line Region. Models of blazar variability suggest that the intrinsic size-scales are very small (light days) in extent.

Therefore, the first steps in microarcsecond astrometry of quasars should focus on understanding of a small number of objects, selected on the basis of known properties. A full statistical study is beyond the scope of SIM, and is best done by a survey instrument such as the proposed European GAIA mission.

Our preliminary target list is shown in Table 5.1. One of the tiles is shown graphically in Figure 6. We have selected seventeen objects, including a fortuitously placed radio star, in four tiles. On the average, there is one ICRF quasar per SIM 15 degree field of regard. We have included several of the nearest and best-studied archetypal quasars and AGN: M 87, 3C 273, 3C 279, and 3C 345. These all have several years of VLBI imaging with a few 100μas resolution. OJ 287 is believed to have the best case for periodicity which might indicate binary black holes.

The selection was based on four criteria applied together: (1) suitability for addressing the science questions in Section 2; (2) AGN of various types which are both radio-loud, and within 7.5 deg of a nominal tile center; (3) available ICRF sources in the tile; and (4) ICRF source magnitude $V < 18$. We can, of course, modify the list if some of the targets become too faint for SIM.

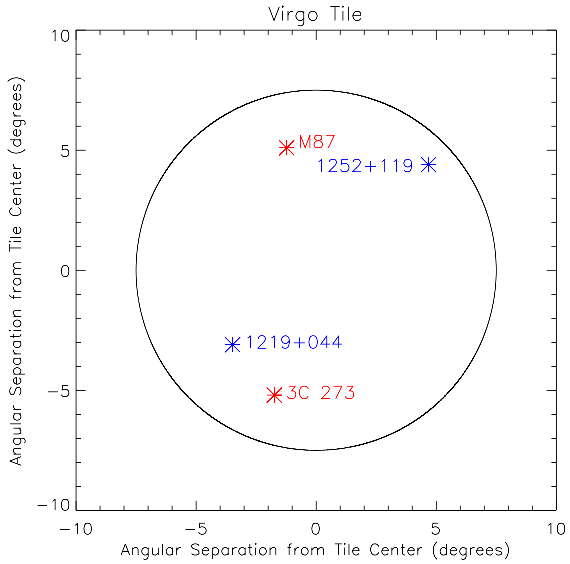

Figure 6: Targets in the Virgo South Tile. Prime science targets are in red; ICRF defining sources are in blue.

Table 1: SIM Target Tiles

Tile Name	Tile Center	Sources	ICRF	V mag	Classification
Virgo North	1233+075	1219+044	Yes	18.0	Quasar
		3C 273	No	12.9	$\gamma-$ray Quasar
		M87	Candidate	(17.0)	AGN 1” core magnitude (Biretta *et al.* 1991)
		1252+119	Yes	16.6	Quasar
Virgo South	1237-005	1219+044	Yes	18.0	Quasar
		3C 273	No	12.9	γ-ray Quasar
		1229-021	No	17.7	γ-ray Blazar
		1243-072	Candidate	18.0	γ-ray Blazar
		3C 279	No	17.8	γ-ray Blazar
Corona Borealis	1633+382	1611+343	Candidate	17.5	$\gamma-$ray Blazar
		σ^2CrB	No	12.0	Radio Star
		1633+382	No	18.0	$\gamma-$ray Blazar
		1638+398	No	16.5	Highly Polarized Quasar
		3C 345	No	16.0	Quasar
		Mrk 501	Candidate	15.2	$\gamma-$ray Blazar
Cancer	0850+250	0827+243	Candidate	17.3	$\gamma-$ray Blazar
		0839+187	Yes	16.4	Quasar
		OJ 287	Candidate	15.4	$\gamma-$ray Blazar
		0912+297	Yes	16.4	BL Lac

5.2 SIM Experiment Design

This science program requires only a modest amount of SIM observing time, about 3%, or about 750 hours. Below, we describe the design of our observing plan, and how we estimated the required observing times. The main experiment design criteria were:

(1) To address the science goals described above, using the minimum necessary SIM time. To do this, we restrict both the number and distribution of targets.

(2) To obtain meaningful scientific results within the first year of SIM operation.

We have shown that SIM's accuracy will exceed the ICRF accuracy realized by VLBI by a substantial factor, and no other instrument besides SIM can do quasar astrometry below ~ 100 μas. Therefore, we do not have to wait for the final solution for the astrometric grid, nor the definitive frame-tie, in order to address the science goals. In fact, relative positions accurate to about $\sigma_{\rm AGN} = 15$ μas, after 1 year, will be adequate. $\sigma_{\rm SMA}$ is the (RMS) single measurement accuracy in one astrometric position coordinate; relative position can be measured in a single tile "visit", and will improve on repeated visits.

The *observational* goals of our AGN program require: (1) Relative positions and proper motions between AGN of several different classes; and (2) Color-dependent position offsets using differential phase information on individual AGN.

We can achieve all of these goals by limiting our target selection to those which "fit" within a small number of SIM tiles. Since our science objectives can be met using *relative* measurements between AGN, we place only limited reliance on the astrometric grid constructed by the SIM Project. Thus our observing plan does not require global astrometry; instead we perform local astrometry within a single tile. And because we do not depend on the grid, we can obtain results in the first year, when the anticipated grid accuracy will be much poorer than at end-of-mission.

By concentrating the observations within a tile, we gain over the standard wide-angle observation scenario, both in terms of reduced observing overhead, and improved instrument performance. While the selected AGN are too faint to enable the rapid-switching which will be used for planet-searching, we avoid picking up astrometric errors from the grid itself.

5.3 Tile observation sequence

Each tile will be observed in a time-efficient manner which shares characteristics of both standard narrow- and wide-angle SIM modes. That is, we observe grid stars to determine the basic instrumental parameters, followed by the science targets. A representative timeline is shown in Figure 7. Depending on the instrument stability over $\sim$ hour timescales, we may repeat the grid star observations at the end of a tile, to eliminate first-order drifts. AGN positions will be computed in the coordinate frame of the grid, and refined as the grid improves during the mission. But the science will be derived primarily from differences in $\sigma_{\rm AGN}$ for each target at the epoch in question.

Because most of our targets are relatively faint, our data will be dominated by photon noise, rather than instrument systematic errors. We estimate the "systematic" part of SIM's single-measurement accuracy to be around $\sigma_{\rm sys} = 7.2$ μas; this includes an estimate of an angle- dependent contribution to the variance σ^2. With a typical observing time of 1200 s on $V = 18$ targets, we expect to achieve a single measurement accuracy of ~ 13 μas.

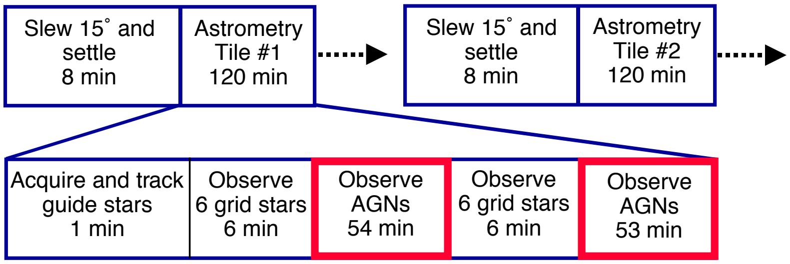

Figure 7: Sample SIM Quasar Observing Timeline.

Thus by design, our experiment is relatively insensitive to the actual value of $\sigma_{\rm sys}$ which SIM achieves.

This makes the generation of an observing plan for a given total observing time mainly a trade between number of observations and astrometric accuracy of each observation. To be sure that the proposed plan remains in this regime, we computed an efficiency metric of $\sigma_{\rm AGN}\sqrt{t}$ which would be constant for an ideal instrument. Long integrations are inefficient because of instrument systematics; very short observations are inefficient because of per-target overhead.

There will be also random contributions to the astrometric error from errors in the solution for the SIM baseline, as derived from the grid stars. We assume that after 1 year the grid accuracy will be $\sigma_{\rm grid} \sim 15\,\mu$as; this includes an estimate of systematic errors which will eventually be calibrated. But since we perform relative measurements, i.e., angular separation within a tile, we are insensitive to errors in the baseline due to this: the size of this effect is proportional to field size, and simulations have shown that for planet-searching within a 1-degree radius field, the effect is well below 1 μas can can safely be ignored. If necessary, we can improve the baseline solution by observing, say 10 instead of the nominal 6 grid stars in a tile (on average, the grid will contain 12 - 13 grid stars around any given tile center). This would cost very little additional mission time (a few minutes per tile).

The basic parameters of our observing plan are summarized in Table 2, for a representative tile with three $V = 18$ quasars. Slew time to a tile (conservatively) assumes a 15 deg rotation about the largest moment of inertia axis. The end-of-mission astrometric accuracy is only weakly dependent on many of the parameters. We expect to do a more detailed simulation pre-launch, including a more realistic instrument model and an optimized observing sequence.

5.4 Monitoring time dependence of astrometric positions

Active galaxies can have variability timescales spanning a huge range. We have opted to follow variations on timescales no shorter than one month, for reasons of SIM observing time. We will observe each tile monthly for 8 months each year (sun-avoidance restricts the observing windows). Each tile will be observed in 2 orthogonal directions every month. This strategy is well-suited to obtaining early, “standalone” science results in the first year. It will, of course be possible to modify strategy for years 2 - 5 in the light of first year’s results.

Table 2: Factors Determining SIM Observation Time

Tile parameters	Slew time to tile	735 s
	Grid star observing time (6 grid stars, every 60 minutes)	360 s
	Number of AGN targets per tile	5
	Assumed AGN magnitude	$R = 17.5$
	Integration time per AGN	1200 s
	Overhead per integration	40 s
	Single measurement accuracy (1-D) (relative to tile reference frame)	13.2 μas
Mission parameters	Mission accuracy in position (1-D)	5.6 μas
	Number of tile visits in first year	8 × 2 orientations
	Total tile visits (5 years)	40
	Mission time per tile	186 hours
	Number of tile centers	4
	Total mission time	745 hours

The total observing time we request is approximately 3% of the SIM mission, for a total of about 750 hours. This corresponds to about 2.3 hours per tile visit, including overhead. Our choice of number of targets and desired accuracy was matched to tile visits of approximately this length.

5.5 Color-Dependent Differential Astrometry

The ability of SIM to detect fringes in 80 spectral channels allows very precise measurement of the angular separation between regions emitting different color light within the same source. This is a differential measurement, whose precision depends on the SNR of fringe detections within each subset of the total wavelength range but does not depend on the accuracy of the angle measurements between sources or the total wavelength range used to determine individual group delays.

The important quantity for color-dependent differential astrometry is not the group delay, but the phase shift between fringes in adjacent sets of spectral channels. Measurement of this phase shift requires that fringes be stabilized on the detector array, but the phase shift is unaffected by the value of the group delay or its uncertainty. Fringe phase is a far more powerful observable than group delay because it does not require a large fractional wavelength range to provide precise information on color dependent position shifts.

The simplest color-dependent differential astrometry experiment involves dividing the 80 available spectral channels into "red" and "blue" groups. By averaging fringe phase over each group, the offset (if any) between the centroids of the red and blue light can be found from the difference in the averaged phases. To first order, the astrometric accuracy in one group would be degraded a factor of $2\sqrt{2}$ relative to the full band, due to (1) half the photon count, and (2) doubling of the length of the white-light fringe envelope. The difference between red and blue delays should therefore be be a factor ~ 4 less accurate that the broad-band delay.

This measurement should be extremely robust. The red-blue phase difference should be almost immune to guiding, feed-forward errors, and vibrations, limited primarily by photon noise. If such shifts exist, they should be easy to detect at a level of 15 μas in even a single measurement of an AGN.

Fringe extraction for color-dependent delay requires careful simulation, and we plan to do this as part of our preparatory science. In order to compute astrometric delays as a function of color, we require that the spectrally dispersed fringe data be telemetered to the ground without on-board channel averaging. We understand this will, in fact, be the normal operating mode for the science interferometer.

We will also simulate the detectability of detecting a phase shift in a strong spectral line such as Hα against the nearby continuum. This is closely related to spectral line imaging; detailed simulations of a large (0.25 arcsecond) disk at the distance of M87 by Böker and Allen (1999) have shown that a target which is *spatially* resolved, as well as spectrally resolved, can be imaged in a bright spectral line. For the AGN we observe at moderate redshift, we would not expect to detect a change in the visibility amplitude, but *shifts in the phase should be readily detectable.*

5.6 AGN and the Frame Tie of SIM to the International Celestial Reference Frame

The goal of tying the SIM grid into the International Celestial Reference Frame requires observations of selected AGN over the whole sky. The tie will be done using an optimized, maximally consistent solution of the SIM grid simultaneously with the AGN data, assuming zero parallax and proper motion for the AGN. This frame-tie task is a responsibility of the SIM Project. However, the data we obtain for our science goals will be very important in two respects:

(1) Our data can be used as part of the AGN dataset which ties SIM to the ICRF. For this reason, we will *not* request that our target quasar data be proprietary, instead, we will make it available for this purpose.

(2) Our scientific results will provide an early indication of the expected accuracy of the frame tie. While the assumption of zero parallax is presumably sound, almost nothing is currently known about the microarcsecond-scale structure of AGN. If it turns out that the AGN, for whatever reason, are less astrometrically stable than expected, our science data will show it within the first year of SIM operation. While this does not offer a solution, should a problem arise, it provides an early alert to the SIM Project that a modified observing strategy and/or target list of AGNs is needed.

6 Milestones

The milestones indicated below are laid out by year, relative to SIM launch. These objectives are described in more detail in the previous Sections.

- L-5 Set up and coordinate collaborations with optical monitoring groups to observe selected AGN to confirm variability timescales. Start phase referencing VLBI experiment on M87 or other AGN to see if there is motion of the radio core. Study field stop issues.
- L-4 Continue optical monitoring (from L-5 to L+5) Run SIM-SIM experiment to simulate our observing program. Refine observing strategy based on SIM-SIM results. Conduct second-epoch phase referencing experiment.
- L-3 Observe targets with Keck Interferometer to verify that source structure is not a problem with resolution similar to SIM's. Write paper on phase-referencing VLBI experiment.
- L-2 Observe second-epoch and second-season targets with Keck Interferometer. Obtain good optical and radio positions for all targets with USNO or VLBA. Work with FAME team to evaluate data on brightest quasar targets. Write paper on Keck Interferometer data.
- L-1 Hire postdoc. Make arrangements to monitor optical fluxes intensively, synchronize with probable SIM observing schedule ("observe at night"). Finalize observing strategy and deliver target list to SIM Project.
- L+0 SIM Launch. Observe first tile in first 6-months during In Orbit Checkout. Begin monthly observations (modulo sun constraints) for four tiles. Coordinate with Project's frame tie effort. Validate Project frame tie strategy by analyzing our first dataset. Perform contemporaneous VLBI phase-referencing (through end of mission).
- L+1 Finish first year of observations. Publish result on targets in first tile region. Communicate results to Project to enable them to optimize frame tie strategy. Modify observing strategy as needed.
- L+2 Commence long-term observing plan. Update database of observed angular separations. Publish analysis of targets in second, third, and fourth tile regions.
- L+3 Evaluate data for binary black hole motion (eg., orbital motion). Evaluate changing separation between optical AGN in each tile and separation of optical photocenters from radio cores. Publish analysis of separation changes.
- L+4 Repeat L+3 activities.
- L+5 End of Mission. Recalculate all positions at each epoch using all our data. Compare positions derived from our data to those derived with full Grid. Publish comparison.

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Education and Public Outreach

Astronomy holds a strong fascination for the general public. Black holes and quasars, in particular, attract considerable attention.

We see astronomy as an important way of engaging the public interest in science, and the physical sciences in particular. Astronomy provides a "hook" for motivating students to pursue mathematics. We plan to capitalize on the inherent interest in the subject in reaching out to a group underrepresented in the physical sciences, namely, women. The PI, Dr. Ann Wehrle, and her Co-Investigators, are strongly committed to this education and outreach effort.

We are enthusiastically committed to devoting a fraction of our research efforts to education and outreach. The NASA-AO-expected level of effort, 5% of funded support, is about $10,000 a year in real-year dollars for our proposal. We are pleased that SIM will have an Outreach Scientist to develop an E/PO program by leveraging off effective programs wherever possible, and avoiding duplication of effort.

We look forward to working with the Outreach Scientist, and the SIM Project's E/PO program, in developing and implementing a long-term E/PO strategy for SIM. We will volunteer to see the SIM E/PO includes an element that addresses the particular education issue of science and math for girls. Dr. Wehrle, with two young children of her own, has worked with elementary school teachers in the Pasadena area. She is developing curriculum use of books that show young women taking active roles, such as flying airplanes or commanding the Space Shuttle. She has also spoken with Los Angeles-area undergraduates and graduate students about combining work and family life. With fellow alumnae of Bryn Mawr College, she is contributing to a web site for young women scientists on work and family life solutions. Three percent of Bryn Mawr women major in physics; this rate is nearly 50 times the national average for women graduating with undergradute physics degrees in the United States.

These examples show the PI is already actively engaged in and committed to outreach efforts in science and math.