Executive Summary

Science Investigation: Masses and Luminosities of X-Ray Binaries

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

- Determine the orbits of two black-hole candidates to measure the black hole masses.
- Obtain precise mass measurements for two neutron star systems to constrain neutron star equations of state.
- Determine the distances and thus luminosities of selected representatives of various classes of X-ray binaries (black-hole candidates, neutron stars, jet sources, ADAF sources).
- The same observations will also yield proper motions, from which the age of the population can be estimated.

Mission Scientist Functions: Support of Grid and Reference Stars, and Global Error Analysis

The PI, Andreas Quirrenbach, proposes to support the selection of grid and reference stars for SIM, to help ensure that these stars are free of astrometric wobble due to undetected companions, and to participate in a global error analysis that takes into account both astrophysical and instrumental sources of error. He will work with the ISDC and the SIM Project to define the selection criteria for the SIM grid stars, and the ground-based observing program required to produce the final grid star list. He will simulate the expected contamination by binaries and companions that escape detection prior to launch. He will assist the PIs of all narrow-angle observing programs to identify their requirements for reference stars, and help ensure that they are met. He will participate in the on-orbit performance verification, and in the identification of individual problematic grid and reference stars. He will ensure continuity of the grid star program over the whole lifetime of the mission. Quirrenbach brings the following set of experience and skills to the SIM Science Team:

- Hands-on experience with optical interferometers, including a proven track record on their scientific use, and on design of new instruments.
- Profound familiarity with technical and astronomical issues pertinent to optical interferometry and to SIM.
- Team and project management experience.
- PI on SIM grid star project which has demonstrated a promising approach to finding a suitable set of grid stars (distant K giants).
- Long-term commitment to SIM.

Science Investigation and Technical Description

Masses and Luminosities of X-Ray Binaries

X-ray binaries are among the most fascinating objects in the Galaxy. They are characterized by accretion of material flowing from a main-sequence or post-main-sequence star to a compact object. Substantial effort has been devoted to estimates of masses in X-ray binaries using visible radial-velocity data and timing of X-ray pulsations. In several cases, these mass estimates have provided convincing evidence that the mass of the compact object is $> 3\,\mathrm{M}_\odot$, a generally accepted upper limit on the mass of neutron stars. This class of object is therefore known under the label "Black Hole Candidates" (BHCs), as the compact object is most likely a stellar-mass black hole. In other systems, X-ray pulsations show clearly that the X-ray component is a neutron star. In these cases, dynamical information can be used to determine limits on the mass of the neutron star, which gives important constraints on the equations of state of neutron star matter, and on the evolutionary path that leads to the formation of these objects. The central issue for these efforts is the conversion from observables (radial velocities or timing data, which yield mass functions) to masses. For X-ray pulsars, it is possible to observe the line-of-sight motion for both binary components. This provides a direct measurement of the mass ratio, $q = M_X/M_{\mathrm{opt}}$, but a measurement of the binary inclination (i) is still necessary to determine the neutron star mass. For BHCs, current methods do not provide a measurement of the line-of-sight motion for the X-ray component in these systems, and compact object mass measurements rely on somewhat indirect estimates for q and i.

Another problem arises from the fact that the distances of most X-ray binaries are poorly known. The resulting uncertainty in the luminosity introduces additional complications for the modeling, and renders arguments based on comparison with the Eddington limit somewhat dubious. Furthermore, it has been argued that BHCs should have lower luminosities in quiescence than neutron stars, due to the lack of a solid surface. Such comparisons, as well as detailed tests of theoretical scenarios such as advection-dominated accretion flow (ADAF) models depend on good luminosities and therefore on uniform and reliable distance estimates. The uncertainties in i, q, and luminosities leave a number of important questions open:

- Can we convincingly demonstrate the presence of an event horizon in BHCs, which would prove the existence of black holes?
- Are the luminosities of BH candidates compatible with ADAF models?
- What is the mass distribution of BHCs?
- Are there any low-mass ($\lesssim 5\,\mathrm{M}_\odot$) BHs, which may have formed via accretion-induced neutron star collapse?
- Are there any high-mass ($\gtrsim 20\,\mathrm{M}_\odot$) BHs, whose progenitors succeeded in retaining most of their mass until collapse?
- Can we place empirical constraints on the spin of the black holes?
- Can neutron stars be significantly more massive than $1.4\,\mathrm{M}_\odot$? This would place interesting constraints on the neutron star equations of state.
- Do proper motions indicate that low mass X-ray binaries have reached an equilibrium, with as many moving toward the Galactic plane as away from the Galactic plane, implying that they are an old population?

SIM offers unique capabilities that can address these issues. In narrow-angle mode we can directly determine the optical orbit, which immediately gives i. In addition, the semi-major axis places constraints on q. If the line-of-sight motion of the compact component can be observed, and the visible light is dominated by the other component, q, and therefore the masses, can be determined directly. This is the case for many neutron star binaries. If the visible light is contaminated by emission from the accretion disk, or the line-of-sight-motion of the compact object is not easily observed (as in BHCs), the observed astrometric motion can be used as an additional constraint in models for determining q. Wide-angle observations can easily give parallaxes with $\sim 10\%$ accuracy even at 10 kpc, and therefore luminosities to $\sim 20\%$. Proper motions will be measured much more accurately than needed for kinematic studies of the X-ray binary population.

Properties of X-ray binaries

X-ray binaries are usually separated into two classes, high mass X-ray binaries (HMXBs) and low mass X-ray binaries (LMXBs) depending on whether the mass of the stellar component (i.e., the optical companion) is greater than or less than $1\,M_\odot$ (see White et al. 1995 for a comprehensive review of X-ray binaries). For both types of systems, the closest sources are at distances of approximately $1-2$ kpc. HMXBs have long orbital periods (typically days to years), wide orbits and are optically bright, making them good targets for orbital measurements with SIM. For these systems, the optical light is dominated by the optical companion, so that, to a good approximation, SIM will measure the orbit of the optical companion. Although many HMXBs are X-ray pulsars, some well-known BHC sources are HMXBs (e.g., Cyg X-1). Most LMXBs contain M or K-type stars, and have orbital periods from hours up to a day. Their small orbits make SIM narrow-angle observations challenging. Also, for LMXBs that are persistently bright in X-rays, significant optical light comes from both binary components. Although orbital studies of these systems will be difficult with SIM, distances and proper motion measurements will be very useful.

For several HMXBs, it has been possible to measure line-of-sight velocities for the neutron star and the optical companion (van Kerkwijk et al. 1995b). These velocities are characterized by the semi-amplitude for the radial velocity curve (K_X for the neutron star and $K_{\rm opt}$ for the optical companion). The eccentricity of the orbit can be determined from the shape of the radial velocity curves. The binary inclination i is also necessary to measure the neutron star mass, and, for relatively high inclination systems, it can be inferred from the duration of the eclipse of the neutron star. Although K_X can be measured very accurately, there is significant uncertainty in the measurement of i and some uncertainty in the measurement of $K_{\rm opt}$. Due to these uncertainties, it is only possible to measure the neutron star mass to $30\%-50\%$, which is not useful for constraining neutron star equations of state. As described below, SIM provides a direct measurement of the neutron star mass for systems where K_X is known.

For LMXBs that are strong and persistent X-ray emitters, but do not exhibit X-ray pulsations, it is not possible to measure K_X or $K_{\rm opt}$. This is true because the optical light is dominated by X-ray reprocessing in the accretion disk and the side of the optical companion exposed to the X-ray source, masking the absorption lines that would otherwise be seen from the optical companion. Rather than being persistent sources of X-ray emission, some X-ray binaries produce only transient X-ray emission. When these systems are in quiescence, it is possible to measure $K_{\rm opt}$ from the Doppler shifts of the absorption lines from the optical companion (see Charles 1998 for a review). Although $K_{\rm opt}$ alone provides a lower limit on the compact object mass, more information is necessary to actually measure the compact object mass. The following equation shows the parameters that must be determined to measure the compact object mass

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

where $f_{\rm opt} = PK_{\rm opt}^3/2\pi G$, P is the orbital period and i (the binary inclination) and q (the mass ratio) are described above. Although P

is easily measured to high accuracy, measurements of i and q are more indirect. The inclination can be estimated because tidal effects from the compact object cause the companion star's shape to be distorted from spherical. The distortions cause the flux to be modulated at twice the orbital frequency, and the amplitude of the modulations (often called "ellipsoidal modulations") is strongly dependent on the binary inclination (see e.g., Orosz & Bailyn 1997). Thus, differential photometry can be used to measure the binary inclination, but this measurement relies on modeling the light curve. In cases where there is significant X-ray heating in quiescence, this modeling is subject to considerable uncertainty. The methods used to estimate the mass ratio (q) are also somewhat indirect and are described in Casares & Charles (1994). However, the main uncertainty in the derivation of compact object masses is the error in the measurement of the binary inclination.

The BHC masses measured to date suggest a distribution concentrated near $7-10\,\mathrm{M}_\odot$, and a surprisingly wide gap between neutron star and BHC masses (see Figure 1). The BHC mass distribution has important implications for the evolution of BHC X-ray binaries. Work by Brown, Lee & Bethe (1999) suggests that BHCs with masses considerably lower than $\sim 7\,\mathrm{M}_\odot$ may exist, but these may be quite rare. These authors suggest that there is a dichotomy in the evolutionary tracks of binaries that depends on the mass of the BHC progenitor. Their evolutionary scenario predicts that massive ($\sim 40\,\mathrm{M}_\odot$) progenitors will form BHCs with masses near $2\,\mathrm{M}_\odot$, while the lower mass and more common progenitors ($20-30\,\mathrm{M}_\odot$) will form $\sim 7\,\mathrm{M}_\odot$ BHCs. Accurate BHC mass measurements are critical to test such theories.

It should be noted that the method used to measure planet masses cannot be used to measure the masses of compact objects in X-ray binaries. Specifically, in measuring the mass of a planet, one can assume that the mass of the parent star can be determined reliably from a determination of its spectral type. However, for X-ray binaries, the optical companion is strongly influenced by the presence of X-ray emission and tidal forces from the compact object. It is likely that even a low level of X-ray heating of the optical companion could change the spectral type inferred from optical spectroscopy. Thus, in general, the mass of the optical companion cannot be easily determined.

The parallax of the LMXB Sco X-1 has been measured at radio wavelengths using the Very Long Baseline Array (Bradshaw, Fomalont & Geldzahler 1999). The value $360 \pm 40\,\mu$as, corresponding to a distance of $2.8 \pm 0.3\,$kpc is the most precise trigonometric parallax measured to date. It represents an upward correction of the best previous distance estimate by 40%. Sco X-1 is a member of the class of so-called "Z sources", which are characterized by a Z-shaped pattern in X-ray color-color diagrams. The parallax measurement for Sco X-1 supports a model of Eddington luminosity for Z sources at the normal-flaring branch vertex of the color-color diagram. SIM could confirm this finding for other Z sources, determine the spread in luminosity, and thus determine whether Z sources can be used as X-ray standard candles.

Distance estimates of other X-ray binaries are much more indirect. For example, Predehl & Schmitt (1995) show that optical extinction and X-ray absorption of cold gas are closely correlated. It is therefore possible to get rough distance estimates from the absorption in the ISM. Parallaxes from SIM would provide much better distances, and would in turn provide information about the ISM (for details see Predehl & Schmitt 1995).

Mass Determination with SIM

As described in the previous section, accurate and direct measurements of the masses of compact objects in X-ray binaries are not currently available. For HMXB X-ray pulsars and X-ray transients, the primary difficulty is the measurement of the binary inclination. In some cases, the inclination can be estimated from X-ray eclipse durations, polarization variations or photometric variations, but the error in the inclination is still the largest uncertainty in the mass determination. Since SIM observations will provide a very accurate measurement of the binary inclination ($\sim 1^\circ - 2^\circ$), such observations will provide greatly improved constraints on compact object masses. Also, SIM observations will provide a useful check on the less direct methods for measuring binary inclinations.

Using SIM in narrow angle mode and observing the binary 30–40 times will allow for an accurate astrometric orbit determination. This will provide the Thiele-Innes constants, i.e. the semi-major axis of the orbit of the photocenter relative to the center of mass, $a_{\rm phot}$ (in angular coordinates from the orbit solution and as an absolute length in combination with the parallax), the inclination i, the longitude of periastron ω and the position of the ascending node Ω. The period and the eccentricity could also be inferred, although the period usually is very well known from X-ray observations or optical photometry, and the eccentricity can be derived from radial velocity observations.

SIM observations of HMXB X-ray pulsars, along with currently available information from X-ray and optical observations, will provide a accurate and direct measurement of all orbital parameters, including the mass of the neutron star. tThe only parameter that still remains undetermined is the inclination i, which will be provided by measuring the astrometric orbit with SIM. Thus, X-ray observations, optical spectroscopy and SIM astrometry complement each other in an ideal way.

Probes of Strong Gravity and Black Hole Spins

Quasi-periodic oscillations (QPOs) are temporal variations in X-ray flux that are detected as peaks in Fourier power spectra. QPOs are detected at frequencies between 0.01 Hz and 300 Hz for nearly all accreting BHCs at least some of the time. High frequency QPOs (above 50 Hz) are the most interesting and have only recently been discovered by the *Rossi X-ray Timing Explorer.* Although several QPO mechanisms have been suggested, the mechanism operating in accreting BHCs is not known. Most suggested QPO models rely on effects of General Relativity, providing the potential for testing GR in the strong field limit. The predictions of QPO models depend on BHC masses and spins; thus, BHC mass measurements from SIM can directly contribute to this work. As an example, the existence of a MSO (i.e., an orbit inside of which there are no stable circular particle orbits) is a key prediction of GR that has not yet been verified. This orbit is at a distance from the black hole that depends on the mass and spin of the black hole (3 Schwarzschild radii for a slowly rotating black hole). The 300 Hz QPO observed for the BHC X-ray transient GRO J1655–40 (Remillard et al. 1999) originates from a region very close to the MSO based on the fact that 300 Hz corresponds to the dynamical (i.e., Keplerian) time scale at the MSO for a slowly rotating $7\,{\rm M}_\odot$ black hole. Mass measurements using the techniques described above do, in fact, indicate that the mass of the GRO J1655–40 compact object is close to $7\,{\rm M}_\odot$, but reliable black hole spin measurements are not yet available. Verification of the compact object mass for GRO J1655–40 and mass measurements for other systems with QPOs using SIM are very important for these studies.

Equations of State from Neutron Star Masses

Neutron stars provide an opportunity to learn about the densest matter in the universe. The core density of a neutron star is higher, possibly by an order of magnitude, than nuclear densities. Currently, there is significant uncertainty about the properties of neutron star ma-

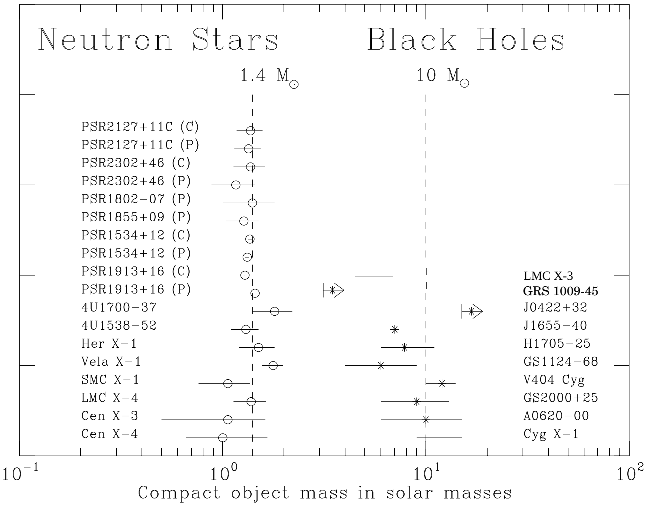

Figure 1: The distribution of measured masses of neutron stars and black holes. Black holes plotted with asterisks are the X-ray transients. The theoretical upper mass limit for neutron stars is $3.2\,M_\odot$ (Rhoades & Ruffini 1974). Adapted from Miller, Shahbaz & Nolan (1998).

terial. The specifics of the composition of the neutron star material (e.g., are neutron stars made of neutrons, protons and leptons or does the material include hyperons, meson condensates and/or quark matter at the high densities that occur in neutron stars?) and the dynamics of the material lead to different predictions for neutron star equations of state (EOS). Observations can constrain EOS because each EOS predicts a different relationship between the mass and radius of neutron stars (see Shapiro & Teukolsky 1983). In addition, for each EOS, there is a maximum possible neutron star mass that can be supported. The "stiffest" EOS have maximum masses near $2.7\,\mathrm{M}_\odot$, while the "softest" EOS have maximum masses of $1.5\,\mathrm{M}_\odot$, which is barely above the Chandrasekhar limit for white dwarfs. Thus, finding a neutron star with a mass higher than $1.5\,\mathrm{M}_\odot$, for example, will eliminate the softest EOS. It is important to note that an accurate measurement of *one* neutron star mass is sufficient to place constraints on neutron star EOS. In addition, since the neutron stars in X-ray binaries are accreting, they are likely to provide the highest neutron star masses and therefore the tightest EOS constraints. Accurate mass measurements are available in the case of double neutron star radio pulsar systems (see Figure 1). However, it is doubtful that these neutron stars went through an accretion phase.

Current estimates of neutron star masses in X-ray binaries have large uncertainties (30-50% in the best cases). One example is Vela X-1, where the neutron star mass is $1.88^{+0.69}_{-0.47}\,\mathrm{M}_\odot$ (van Kerkwijk et al. 1995b). The large uncertainties in the mass measurement come from poor constraints on the binary inclination of the system and the radial velocity of the optical companion. SIM measurements will greatly improve the measurement of the neutron star mass in Vela X-1. The current mass measurement suggests that the mass may be well above $1.4\,\mathrm{M}_\odot$. If the SIM measurements show that this is the case, it will be possible to eliminate several candidate EOS, enabling us to learn about the properties of high density material.

Jet Velocities

Jets of material moving at relativistic speeds away from compact objects are a common but poorly understood phenomenon. Such jets are observed at radio wavelengths, and it has long been known that Active Galactic Nuclei (AGN) produce jets with velocities close to the speed of light. It is now known that relativistic radio jets are also produced by Galactic compact objects. One of the first and best studied Galactic jet sources is SS 433. For this system, the jet velocities are close to 0.26 c (Margon & Anderson 1989). Jets with much higher velocities have been observed for Galactic sources recently. There are four systems where the jet velocities are estimated at greater than 0.9 c, and these systems are called "microquasars" because of their similarity to AGN. For the first microquasar that was discovered, GRS 1915+105, the velocity was originally estimated at 0.92 c (Mirabel & Rodriguez 1994). However, this value assumed a source distance of 12.5 kpc, which was estimated from 21 cm absorption of atomic hydrogen along the line of sight. It is now thought that the distance is somewhat less, between 7 and 12 kpc (Fender et al. 1999), which implies that the jet velocity may be anywhere between 0.7 c and 1 c (see Figure 6 in Fender et al. 1999). In summary, there are currently seven X-ray binaries with relativistic radio jets, and accurate distances are critical for determining the exact velocities and energies of the jets. Using SIM it will be possible to obtain source distances for at least four of the jet sources (GRO J1655–40, XTE J0421+560, SS 433 and V4641 Sgr).

Luminosities

We will select $\sim$ 50 targets for a wide-angle observing program, including these jet sources. The other systems will be selected to represent the different classes of X-ray binaries: Z sources, atoll sources, X-ray sources in quiescence, and the high-latitude sources Her X-1 and XTE J1118+48. This will allow us to check the Eddington assumption, and to compare the luminosities of different source classes. Of particular interest is a systematic comparison of the luminosities of BHCs and neutron stars in quiescence. It is expected that BHCs are fainter because of the lack of a solid surface, i.e., the presence of an event horizon. This hypothesis has not been conclusively tested so far, because of the difficulties in obtaining precise and homogeneous parallaxes. Our SIM observations could therefore make a seminal contribution to the question whether black holes do actually exist in nature.

We will select short-period binaries so that the orbital motion does not affect the determination of parallax and proper motion. The targets range in brightness from $V = 12$ to $V = 18$, with most of the sources at $V = 15 - 16$. About 20 one-dimensional observations per star are needed. We will spend $\sim$ 1 hour of mission time per star independent of the brightness (perhaps with the exception of a few high-priority targets, which could get some additional observing time). This will result in a 15 μas mission accuracy at $V = 16$, and 10 μas at $V = 15$. These numbers translate into $\sim 10 - 15\%$ parallaxes even for the most distant sources, a huge improvement over the current state which is often not better than a factor of a few. The whole wide-angle program will take about 50 hours of mission time.

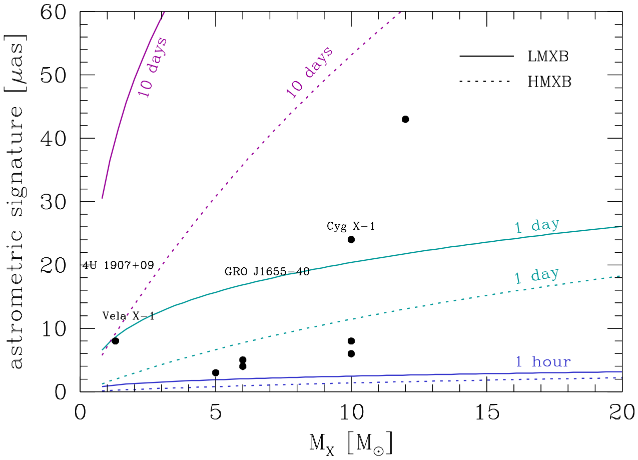

Figure 2: Expected astrometric signature for X-ray binaries. Only sources for which good mass estimates are available today have been included. The solid lines give orbital periods of LMXBs (typically $M_{\rm opt} = 0.5\,M_\odot$), the dotted lines of HMXBs (typically $M_{\rm opt} = 15\,M_\odot$) at a distance of 2 kpc.

Proper Motions / Galactic Distribution

As a by-product of the wide-angle observations we will obtain the proper motions of all targets (10 km/s at a distance of 10 kpc corresponds to 250 μas/yr), another important source of information. van Paradijs & White (1995) have analyzed the Galactic distribution of neutron star LMXBs. They found that the dispersion of the height z above the Galactic plane is 1 kpc, which can only be explained if the neutron star received a kick velocity during its formation, e.g. due to an asymmetry in the supernova explosion. However, for BHC LMXBs, the dispersion is only about 400 pc, more than a factor of 2 smaller compared to that of systems with a neutron star (White & van Paradijs 1996), so that any potential kick velocities must be accordingly smaller. These studies can put important constraints on the formation mechanism for black holes as well as neutron stars.

In addition, the proper motions of these systems carry important information about the age of the population. For a young population, the majority of the sources is expected to move away from the galactic plane, whereas for an older population in dynamical equilibrium about half of the sources should move towards the galactic plane. For a recent application of this line of arguments towards millisecond pulsars, see Toscano et al. (1999). Accurate distances and proper motions are necessary for these studies. Currently they are severely limited by the small number of systems with reliable distance and systemic velocity estimates (e.g., there are only 9 BHC LMXBs with radial velocity measurements). The wide-angle observations will dramatically improve this situation.

Potential Targets for Mass Determination (Narrow Angle Observations)

It is quite likely that new X-ray binaries will be discovered before the launch of SIM, and that better data will be available for the presently known systems. We have therefore decided to present a strawman observing program: we have selected four targets that would be very interesting to observe in detail, based on our knowledge today (Table 1). At the time of the launch of SIM, we can either decide to observe these systems, or to replace one or more targets by more promising sources. Two of the targets in the strawman program are black hole candidates and two are HMXB X-ray pulsars. The purpose of the observations is to determine orbital parameters, and the required astrometric accuracies can only be achieved in narrow angle mode. We have selected systems that are known to be relatively nearby and thus give large astrometric signatures (see Figure 2). We expect that we will be able to obtain errors on i of order $1^\circ - 2^\circ$ from orbit fits for these objects, which translate in mass errors of a few percent depending on the inclination. This expectation is based on (a) a simulation of fits to mock data and analysis of the χ^2 of the orbit fit, (b) simulations of SIM orbit fits by Sozzetti and Casertano (SIM web page), and (c) our own experience with orbit fits to binary data from the MkIII Interferometer (e.g., Hummel et al. 1995).

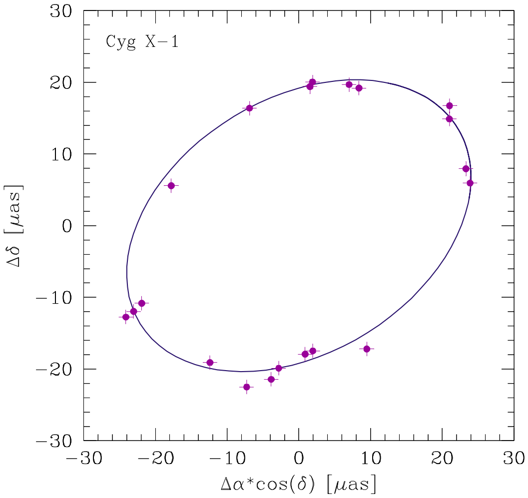

Figure 3: Simulation of SIM observations of Cyg X-1. Estimates of the orbital parameters have been taken from Table 1. In addition, an inclination $i = 47^\circ$ was assumed.

Cyg X-1

Almost three decades ago this system was the first one suspected to contain a black hole. Evidence consisted of analysis of the secondary, an O9.7 Iab star (HDE 226868), and trying to model the orbital parameters for the system, as well as the discovery of its X-ray variability by Oda et al. (1971). The period (P = 5.6 days), eccentricity ($e = 0.0$) and mass function ($f(m) = 0.252$) of the system are relatively well-known (see Gies & Bolton 1996, Ninkov et al. 1987, Herrero et al. 1995). All mass determinations for the compact object are above the threshold for a black hole (the most likely mass is around $10\,M_\odot$), although the individual investigations differ significantly in the exact value.

This is due to the uncertainties in the inclination ($27^{\circ} \leq i \leq 67^{\circ}$, Ninkov et al. 1987), in the distance ($d = 2.5 \pm 0.4\,$kpc, Margon et al. 1973) and in the mass of the visible companion ($5\,\mathrm{M}_{\odot} \leq M_2 \leq 80\,\mathrm{M}_{\odot}$). Both the inclination and the distance could be significantly improved using SIM, which would also lead to a much more accurate and more direct determination of the mass for the compact object. This system is comfortably bright for SIM ($V = 8.9\,$mag), so that exposure times are not a concern. The expected astrometric signature is $26\,\mu$as (assuming that all the light comes from the star), which should allow for precise determinations of the orbital elements.

GRO J1655–40

GRO J1655–40 is an X-ray transient and radio jet source. The first X-ray outburst was detected by BATSE in 1994 (Zhang et al. 1994), with additional outbursts occurring in 1995 and 1996. First dynamical evidence for the black hole binary nature of this object was presented by Bailyn et al. (1995). The period is 2.6 days, the mass function $f(m) \approx 3$, and the companion is believed to be a F subgiant star with a mass near $2\,\mathrm{M}_{\odot}$ (Orosz & Bailyn 1997). Mass measurements for this system are relatively accurate, since the transient nature allows for radial velocity measurements of the companion as well as of light originating in the accretion disk (Soria et al. 1998). However, different attempts at mass determination based on radial velocity measurements and light curve modeling disagree somewhat about the mass and on the likely errors (M_X=7.07±0.22$\,\mathrm{M}_{\odot}$, Orosz & Bailyn 1997; M_X=4.9–6.8$\,\mathrm{M}_{\odot}$, van der Hooft et al. 1997; M_X=4.1–6.6$\,\mathrm{M}_{\odot}$, Phillips et al. 1998; M_X=5.5–7.9$\,\mathrm{M}_{\odot}$, Shahbaz et al. 1999). It has been claimed that the inclination of the system is precisely known from modeling ellipsoidal modulations in the light curve ($i = 69.50 \pm 0.08^{\circ}$, Orosz & Bailyn 1997). However, the inclination inferred from a model of the highly collimated relativistic radio jets is larger, $i = 85 \pm 2^{\circ}$ (Hjellming & Rupen 1995). The difference is not well understood, and a determination of the inclination by SIM will be useful to resolve this conflict. At a distance of about 3 kpc (determined from the dust scattering halo properties, Greiner et al. 1995), the astrometric signature of the companion will be about 19μas.

Vela X-1

Vela X-1 is an eclipsing X-ray binary pulsar with a pulse period of 283 sec. The orbital period is about 9 days, and the optical companion is a B supergiant of about $24\,\mathrm{M}_{\odot}$. There are indications that the mass of the neutron star is higher than the canonical value of $1.4\,\mathrm{M}_{\odot}$, which makes it an interesting target for a precise mass determination. With 6.9 mag the source is bright, and the expected astrometric signature at a distance of about 2 kpc is $12\,\mu$as. Mass determinations from radial velocities yield a neutron star mass of $1.9^{+0.7}_{-0.5}\,\mathrm{M}_{\odot}$(van Kerkwijk et al. 1995a) and 1.77±0.21$\,\mathrm{M}_{\odot}$(Nagase 1989), respectively, although Stickland et al. (1997) conclude from their analysis of IUE spectra that the most likely mass is close to $1.4\,\mathrm{M}_{\odot}$. Precise orbital parameters from pulsar timing analysis are also available (van der Klis & Bonnet-Bidaud 1984, Boynton et al. 1986), which complement the astrometric data.

4U 1907+09

4U 1907+09 is also an X-ray pulsar with a massive companion. The pulse period is 437.5 sec, and the mass function is $f(m) = 9\,\mathrm{M}_{\odot}$ (Makashima et al. 1984). The compact object is believed to be a neutron star with about $1.4\,\mathrm{M}_{\odot}$. There has been some discussion about the spectral classification of the massive companion, which is likely a Be star (with a distance of about 1 kpc). Iye (1986) developed a detailed geometrical model of the system and concludes that the most likely configuration is that of an X-ray pulsar orbiting around a B2e star in an eccentric inclined orbit. This could also explain the two observed X-ray flares during each period of about 8 days. Orbital parameters have been derived by Cook & Page (1987) from pulse timing analysis. At a distance of only 1 kpc, the astrometric signature is 20 μas. This source is heavily extincted, which means that the flux is heavily weighted towards the red part of the visible spectrum. This could in principle lead to systematic astrometric errors; their size has to be assessed by modeling before launch.

Targets of Opportunity and Final Target Selection

Transient X-ray sources offer the opportunity to measure direct masses for both components in a binary system by making measurements of the photocenter motions in different brightness states. While X-ray quiet, most of the visible light comes from the normal star companion, while light from the accretion disk around the compact object dominates during outburst. Thus the effects of the two masses could be separated and individual masses could be obtained with SIM observations alone, without any need for additional radial velocity observations to determine the masses, by measuring the system in both states. Alternatively, SIM observations during outburst could be used to measure K_X, and combined with ground-based spectroscopy during quiescence, which gives $K_{\rm opt}$. Transient sources typically reach a brightness of $V \sim 12$ for several weeks, which makes them well suited for target of opportunity observations. Typical times between two outbursts are 10–20 years for soft X-ray transients and 1–2 years for hard X-ray transients. It is likely that there will be at least one suitable transient at a distance $d \lesssim 2$ kpc during the nominal mission lifetime.

Our preliminary source selection represents the currently most interesting sources where a significant contribution can be expected from mass measurements with SIM. As mentioned above, it is likely that other new interesting sources will be discovered before the launch of SIM. For example, only very recently two transient sources had short X-ray outbursts observed with the Rossi X-ray Timing Explorer, which makes them interesting targets. However, not much is known about the orbits yet, so that it is difficult to estimate whether the expected astrometric signatures will be sufficient for meaningful observations with SIM. V4641 Sgr (Wijnands & van der Klis 2000) is one of the closest sources with inferred jet velocities close to the speed of light, and CI Cam (XTE J 0421+560, Belloni et al. 1999) could possibly harbor a black hole based on the observed radio jets during the outburst.

For other sources (e.g. GX 301–2) the current distance estimates are very uncertain. If the relatively small value of 1.8 kpc is correct, this may be a better target than 4U 1907+09. We will therefore determine preliminary parallaxes from the first two years of the wide-angle observations before deciding about the list of narrow-angle targets. This is possible because the small orbital periods allow all narrow-angle observations to be performed during the second half of the nominal lifetime of SIM.

In summary, there are two systems (Cyg X-1 and Vela X-1) for which a good orbit determination with SIM will certainly be possible. For 4U 1907+09 a detailed assessment of possible systematic errors due to the very red color is necessary. GRO J 1655–40 can only be observed when it is in a bright state. There are a number of other systems (GX 301–2, Sco X-1, CI Cam, V4641 Sgr) that look promising, but require further study from the ground or a parallax measurement with SIM. Target of opportunity observations of a transient source are another possibility. We will decide between these possibilities based on all information available at the time of the observations.

Observing Time

The wide-angle program will need 50 hours of mission time for 50 targets, as described above. For the bright narrow-angle targets, we can

Table 1: Potential targets for narrow angle observations. The first two systems very likely contain a black hole, whereas the last three object probably contain neutron stars. Some basic properties are given (V–magnitude, period, mass and distance estimates). The last column contains the expected astrometric signature (semi-amplitude) under the assumption that all the visible light comes from the companion.

object	V [mag]	P [days]	M_X [$M_\odot$]	$M_{\rm opt}$ [$M_\odot$]	d [kpc]	astr.sign. [μas]
Black Hole Candidates						
Cyg X-1	8.9	5.6	10	20	2.5	26
GRO J1655–40	$15 - 17.2$	2.6	6.9±1	2.34	3	19
Neutron Star HMXB						
Vela X-1	6.9	9.0	1.8	24	1.4	12
4U 1907+09	16.4 [1]	8.37	1.4	12	1	20
(GX 301–2	10.8	41.5	1.4	50	1.8 [2]	13)

[1] Source is heavily extincted. Brightness averaged over SIM passband is ~ 13 mag.

[2] Uncertain. Decision to observe source will depend on SIM parallax.

adopt the sample time line provided on the SIM web page. We will need one hour per visit to reach 1 μas single-measurement precision. About 40 one-dimensional measurements are needed for a good orbit solution; this gives a total observing time of 40 hours per target. At $V \sim 15$ we can modify the sample time line by replacing each 30-second on target observation with a five-minute observation. Leaving everything else unchanged, the on-source integration time is now 3000 s, and the length of the observation 105 minutes per visit (70 hours for 40 data points). Since none of the calibration cycles (between target, reference and grid stars) has been increased by more than a factor of two, the system error should not have been increased by more than a factor of two compared to the sample time line, either. Under this assumption, and taking photon noise of target and reference stars into account properly, the single-measurement precision is 2 μas. Observing two bright ($V < 10$) stars with 1 μas precision, one $V = 15$ star with 2 μas precision, and one intermediate case thus takes $40 + 40 + 50 + 70 = 200$ hours of mission time.

It is thus evident that the scale of the program proposed here is well-matched to an allocation of 1% of the nominal observing time during the primary mission (250 hours). While we can conduct a very interesting astrophysical program within that time, we will pretty much exhaust the “easy” bright targets. Allocation of substantially more time (on the scale of a key project) would lead to rapidly diminishing return because much fainter targets would have to be included. It should also be pointed out that SIM is absolutely necessary for the narrow-angle as well as the wide-angle portion of the program; the precision of other astrometric missions (FAME, DIVA) that may be launched in the same time frame as SIM will not be sufficient in the relevant magnitude range.

The difficulty of the observations varies considerably between the different components of this program. The wide-angle observations are “easy”, the orbit determination for Cyg X-1 and Vela X-1 are well within the nominal capability of SIM, and getting orbits for two additional sources may be at the limit of what SIM can do. There is thus considerable latitude to fine-tune the observing program (before or even after launch) to match the actual performance of SIM. Since all components of the program contain solid and exciting scientific goals, the chances of success are extremely high.

Education / Public Outreach Statement

Black holes are among the most fascinating objects in the Universe; the program proposed here will undoubtedly generate results with a strong appeal to the general public. We will work together with the SIM E/PO scientist to share our enthusiasm with students at the K-14 levels and the general public. We will prepare background information on our findings for public release, and we will actively pursue opportunities for a wide dissemination of the SIM results. Each person funded through this proposal will spend at least 5% of their supported time on E/PO activities.

Description of Mission Scientist (Data Scientist) Functions

Support for Grid and Reference Stars, and Global Error Analysis

Requirements on SIM Grid and Reference Stars

The following sections give an overview of the current status of the plans for identifying grid stars and reference stars for SIM. They serve two purposes:

- We demonstrate that finding suitable grid and reference stars for SIM is a hard (but tractable) and mission-critical task. Consequently at least one of the members of the SIM Science Team should be a grid star specialist.
- We believe that our track record and dedication to the solution of the SIM grid star problem is an important part of the basis on which this proposal should be judged.

SIM is designed to perform astrometry at the microarcsecond level, with one of its main goals being the detection of extrasolar planets. The basic measurements of the interferometer are time delays which can be converted to projected 1-dimensional angular separations of stars once the baseline is known. In order to tie these individual measurements together into a 2-dimensional catalog, a grid of stars with very well determined astrometric parameters is needed. The absolute minimum number of grid stars is about 1000, but currently $3000 - 4000$ stars are envisaged (NASA 1999, Boden 1999) to guarantee the required sky density even if some of the stars should turn out not to be suited as grid stars during the mission.

The astrometric jitter, i.e. the residual non-modeled uncertainty for the positions of the stars, should not exceed $4\,\mu$as for the global grid and $1\,\mu$as for the reference stars which are necessary for increased accuracy close to narrow-angle targets. In addition, the grid stars must not be fainter than 12–13 mag, because otherwise the fraction of SIM observing time dedicated to the grid instead to actual science targets would become too large.

These numbers make it clear that the selection of suitable SIM grid and reference stars is a highly challenging task. There should be virtually no binary stars among the grid sample, because every model for stellar motion with more parameters than position, parallax, and proper motion will severely complicate the precise prediction of positions. Even planetary companions could affect the overall performance of the grid, depending on the distance of the grid stars. Stellar activity and photocenter shifts due to starspots are additional points to be taken into account.

It should be pointed out that it is very costly if the quality of the set of grid and reference stars cannot be guaranteed before launch. If the grid is heavily contaminated by "ill-behaved" stars such as binaries or nearby stars with planetary companions, precious observing time must be devoted to identify them. Even worse, if the motion of a grid star during the mission lifetime cannot be reconstructed from the SIM data with the required precision, any scientific observation for which that star was used as a reference may have to be thrown away. A minimum of four reference stars are needed for each observation to determine the spacecraft attitude. A problem with any one of these stars may render the observation unusable. To safeguard against this, and to avoid such catastrophic loss of observations, one would have to schedule redundant grid star observations *with each science observation.* Note, however, that this is very costly in terms of mission time. For example, the narrow-angle time line published on the SIM web page (which will be used for projects such as searches for extrasolar planets or the X-ray binary program described above) has *no redundancy*, yet specifies that *two thirds* of the elapsed time are spent acquiring and observing reference stars. A $\sim$ 10% contamination of the reference star sample may be acceptable, since then a low level of redundancy would be sufficient. (In that case, five grid star observations instead of the four that are required to solve for the spacecraft attitude would give a success rate of 91.8%, six observations 98.4%). At higher contamination levels, the number of reference star observations required to statistically "guarantee" that four of them are good would increase steeply.

It is thus clear that the quality and integrity of the grid and reference stars is a mission-critical issue for SIM. Consequently, a number of investigations aimed at defining strategies for the selection of grid stars have been funded by NASA through the SIM Preparatory Science Program. The two main alternatives that have been considered are relatively nearby (typically $\lesssim$ 100 pc) main-sequence stars of spectral type A5 to G5, and distant ($\gtrsim 1-2$ kpc) K giants. Arguments for both points of view are given by Frink et al. (2000a, 2000b), Jacobs and Turyshev (1999), Mason et al. (1999), Patterson et al. (1999), Urban et al. (1999), and Wade (1999).

G Dwarfs or K Giants?

G dwarfs have the advantage that they are numerous in astrometric catalogs, and that they are distributed more or less uniformly over the sky. A lot of photometric, spectroscopic and astrometric information is available for them, so that variable and binary stars may be weeded out efficiently.

However, since G dwarfs are not very bright intrinsically, even stars as faint as 12 mag are not located further away than about 300 pc. At this distance, the astrometric signature of Jupiter would still be around 30 μas, much larger than acceptable for the grid. Worse than that, the number of identified G dwarfs beyond 100 pc drops dramatically. At 100 pc, over the SIM lifetime of 5 years, a Jupiter would induce a non-linear astrometric signature of about 100 μas on a solar type star – much larger than acceptable for the SIM grid. However the corresponding radial velocity amplitude (if the orbit is viewed edge-on) would only be 12 $\mathrm{m\,s^{-1}}$. Of course, orbital inclination would serve to reduce the radial velocity amplitude, but not the astrometric signature. Not a single extrasolar planet with a 12 $\mathrm{m\,s^{-1}}$ velocity amplitude has been identified to date. Currently, the extrasolar radial velocity amplitudes are typically 50 $\mathrm{m\,s^{-1}}$ and in the very best cases the detectable radial velocity amplitudes are $20 - 30\,\mathrm{m\,s^{-1}}$. Furthermore, with 10 years of data the radial velocity projects have not detected any planets with orbital radii greater than a few AU (indeed, all but a few are closer than 1 AU). This says less about the actual presence of such planets than it says about biases in detectable separations for Doppler techniques. This means that a Jupiter-mass planet at 5 AU with a nearly edge-on orbit would be just at the detectability threshold with 10 years of very high precision radial velocity data, yet give rise to an astrometric wobble an order of magnitude larger than acceptable. So the detectability of giant planets by radial velocity techniques is dropping precipitously just as the astrometric signature becomes most serious. Therefore, even if the presence of any stellar companion for G dwarfs could be ruled out before the mission, the presence of planetary companions would impose serious problems for the grid. As important as the magnitude of the perturbation is the rate of occurrence of the perturbers around potential grid stars. Planetary companions to solar-type stars may be ubiquitous. What happens to the stability of the grid if nearly all of the G dwarf grid stars have planets?

Late-type giants are also very numerous (in the Hipparcos Catalogue there are about twice as many K giants as G dwarfs) and distributed uniformly over the sky. Stellar companions can be identified just as easily as for solar-type stars, and about the same amount of information is available for them as for the G dwarfs. However, because they are so bright intrinsically, they are on average located at much larger distances than the G dwarfs. A 12 mag K giant would typically be located at 2 kpc, and a 12 mag M giant even at 3.2 kpc. Since the masses of G dwarfs and late-type giants are roughly the same, the astrometric signature of a planetary companion just scales with the inverse of the distance. Thus, the astrometric signature of a planetary companion similar to Jupiter is less than 5 μas for 12 mag late-type giants. A shortcoming for K giants is the fact that a number of them have photospheric motions that result in non-Keplerian velocity variations. These velocity variations do not signal changes in the astrometric position of the star, but those K giants with large amplitude variations originating from the photosphere will be unsuitable grid stars because the presence of low amplitude stellar companions could be obscured by the intrinsic stellar velocity variations.

The bottom line is that intrinsically more luminous stars are better for the grid. If nothing else is known before launch about the grid stars, at any given apparent magnitude the most luminous stars will be affected least by astrometric jitter due to unseen companions. If a radial-velocity survey can be used to weed out companions down to a certain limit, this limit corresponds to a smaller astrometric jitter for the more luminous stars (simply because Doppler variations are independent of distance, whereas the astrometric signature of companions is inversely proportional to distance). The binary frequency of K giants is expected to be comparable to that of G dwarfs, because the progenitors of K giants were late F to early G spectral type, Pop I stars. Stellar companions are relatively easy to detect spectroscopically: even a 0.1 $\mathrm{M}_\odot$ companion with a period of 100 years would show up at the 300 $\mathrm{m\,s^{-1}}$ level. Furthermore, it is known from the Doppler surveys of Marcy, Mayor and their colleagues that brown dwarfs are fairly rare *as companions to Solar-type stars.* Walker et al. (1995) have also shown that planets more massive than Jupiter with orbits of a few years are not common. Because of this "Brown Dwarf Desert" and because Jupiter-like planets give an astrometric signature $\leq 5\,\mu$as, distant K giants are ideal grid stars, provided that one can ensure that they don't have *stellar* companions.

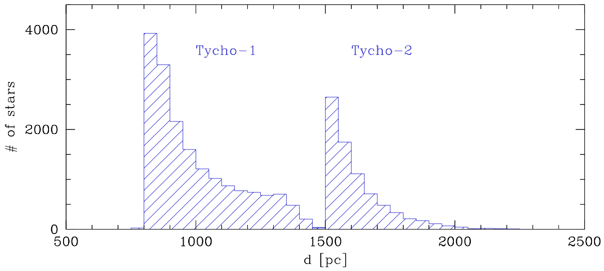

Figure 4: Distance distribution for samples drawn from the Tycho-1 (17 731 stars) and Tycho-2 (7747 stars) catalogs, as discussed in detail by Frink et al. (2000b).

Finding Suitable Grid and Reference Stars

Candidate grid stars can either be drawn from existing catalogs (e.g. Frink et al. 2000b) or be identified in a dedicated observing program (e.g. Patterson et al. 1999). Figure 4 shows the distribution of estimated distance of two samples of bona fide K giants drawn from the Tycho-1 and Tycho-2 catalogs based on photometric selection criteria. The next step is then eliminating binaries with a radial velocity survey. To demonstrate that such a survey is possible, one first has to demonstrate that a sufficient number of stars can be found, in which the level of photospheric variability is low enough to permit precise radial velocity measurements. (The most vehemently voiced argument against using K giants for the SIM grid is based on the notion that this would not be possible.) We have therefore defined a proxy sample of 86 nearby Hipparcos K giants, and started to monitor the radial velocities in this sample with a precision of 5–7 m/s, using the 0.6 m Coudé Auxiliary Telescope (CAT) at Lick Observatory and

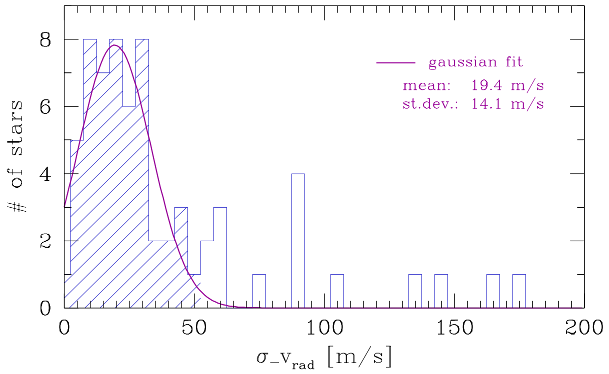

Figure 5: Observed radial velocity dispersions for our proxy sample of nearby Hipparcos K giants (hatched histogram). 6 stars with dispersions larger than 200 m/s are not shown. A Gaussian fit to the data (solid line) reveals a maximum at around 20 m/s. (Updated from Frink et al. 2000b.)

the Hamilton Echelle Spectrograph. This high accuracy is crucial to really assess the level of intrinsic radial velocity variations in our sample.

So far we have been able to get at least three observations for 65 stars over timescales of a few months. 51 stars or 78% of those show radial velocity dispersions smaller than 50 m/s. The distribution of the observed velocity dispersions is plotted in Figure 5 and can be fitted by a Gaussian with a mean of 19.4 m/s and a standard deviation of 14.1 m/s. This result is quite remarkable as it demonstrates that indeed most K giants show radial velocity dispersions considerably smaller than a few hundred m/s over time scales of a few months. We are continuing this program with funding from the SIM Preparatory Science Program; our goals are to quantify selection biases and differences between various samples of K giants, and to explore the time scale of a few years relevant to SIM.

Obtaining a sample of grid stars from which most binaries have been purged is a daunting task, considering that even after pre-selection $\sim$ 6000 stars have to be observed in order to identify 3000–4000 bona fide single stars. (The stars will have to be observed one by one, since they are too sparsely distributed for efficient multi-object spectroscopy.) Assuming that on average 4 observations per star are needed (many of the binaries will already show up with only 2 or 3 observations), a total of $\sim$ 25 000 high-resolution spectra have to be taken. On the other hand, it is worth devoting considerable resources to this task; the only alternative would be using SIM itself to weed out the bad grid stars, which is certainly more costly than doing the best possible job from the ground. The cost of the ground-based program depends strongly on the brightness distribution of the stars chosen for the grid, the specified radial velocity stability, and the availability of additional selection criteria such as photometric stability. We have performed a Monte-Carlo simulation of radial velocity surveys with varying accuracy (see Figure 6), which clearly demonstrates that a cheaper (less precise) survey gives poorer results. On the other hand, the efficiency of high-precision surveys at weeding out binaries is quite remarkable. A number of single stars are eliminated erroneously because of photospheric variability (which means that a larger input sample to the survey is needed), but the contamination is well below 5%!

Proposed Role for PI on the Science Team

Work on the SIM grid is currently funded by the SIM Preparatory Science Program. As the Science Team AO states, “it is assumed that over the next few years the SIM Science Team will take over most, if not all, activities of the Preparatory Program”. Therefore, and because grid and reference stars are absolutely mission-critical for SIM, it is necessary to include at least one person on the Science Team dedicated to ensuring the highest quality of the selected stars. Furthermore, making a grid star specialist a stakeholder in SIM through some guaranteed observing time ensures long-term attention and commitment to grid star and related issues. I propose to take on this responsibility.

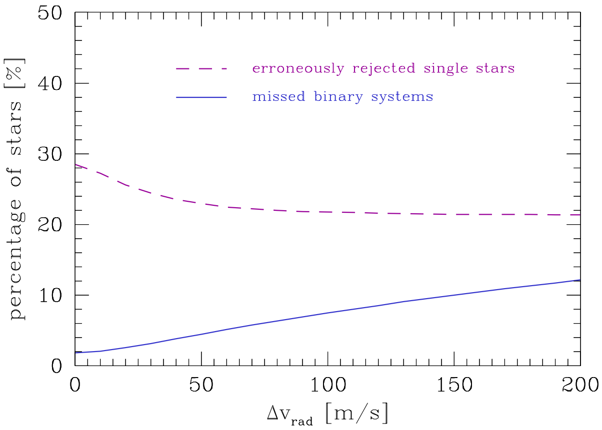

Figure 6: Fractions of missed binary systems and erroneously rejected single stars as a function of measurement accuracy in a simulated radial velocity survey with three observations per star. The results of sets of 1000 simulations have been averaged to obtain these curves. As expected, the fraction of missed binary systems increases with decreasing survey accuracy. For details see Frink et al. (2000b).

The most important grid-related task for the near future is the detailed definition of the ground-based program that will eventually lead to the selection of the ∼ 3000 SIM grid stars. The work performed under the auspices of the Preparatory Science Program has lead to a basic understanding of how this task may be accomplished, and more details will be fleshed out by the existing grants. However, the scope of the actual work needed to take a very large number of high-resolution spectra is very likely incompatible with the cost envelope of the Preparatory Science NRAs (and of the Science Team AO). Furthermore, this task may require a dedicated 3 m class telescope in each hemisphere, or allocation of a large number of nights (dozens per year) on 10 m class telescopes. The details depend critically on the distance of the stars chosen (more distant stars have smaller residual astrometric signature for a given Doppler precision, but are fainter and more costly to monitor), and the specified precision, which in turn determines the residual level of contamination. Sound advice to the SIM Project and NASA requires both a detailed understanding of the grid star selection process, and the consequences for the measurements performed by SIM. It will be necessary to perform a global error analysis that takes into account all instrumental and astrophysical sources of errors.

Based on our current knowledge I would argue that the plan outlined above — selection of a sample of K giants and follow-up with a high-precision radial velocity — is the most promising path to ensure the integrity of the SIM grid. However, it may turn out during the next couple of years that a different strategy is preferable. In that case I would of course urge the SIM Project, ISDC, and SIM Science Team to adopt that strategy. My goal is to obtain the very best grid and reference stars, not to promote a specific approach. In any case, it is likely that a substantial ground-based observing program will be required before launch, so that the need for a grid star specialist on the SIM Science Team remains.

Each narrow-angle program will face the same issues as the grid, namely the selection of suited reference stars. The specifications will vary from program to program, but typically be even more stringent than for the grid stars, because a better astrometric precision is called for. Some programs may be able to provide meticulously chosen reference stars along with their targets, while others may not have the capabilities to do this. (The latter may be true in particular for smaller guest observer projects submitted to later AOs.) It will be necessary to assist the PIs of these programs in devising an optimum observing strategy and in finding suitable references.

After launch it will be important to verify the performance of SIM as quickly as possible. This includes checking the pre-launch estimate of the statistical level of contamination with binaries, as well as the identification of individual culprits so that they can be eliminated from the grid (and replaced with a backup if possible). This process has to be repeated several times over the full lifetime of SIM as binaries with longer and longer orbits may become apparent. Again, this is a task that requires thorough understanding of the grid stars as well as of SIM, since problems with individual grid stars have to be separated from instrumental errors.

In summary, I propose to take on the following tasks within the SIM Science Team:

- Participate in the definition of the exact requirements for the grid stars (number, sky distribution, brightness, astrometric tolerances).
- Provide advice to the SIM Project and ISDC regarding the strategy to define the final selection criteria grid stars (class of star, identification of initial set from catalog or dedicated program, selection mechanisms).
- Assist with the definition and optimization of the ground-based observing program required to draw up the final list of grid and reference stars; this includes identification of suited observing facilities or planning of dedicated instrumentation.
- Provide advocacy for adequate resource allocation to the grid and reference stars, if necessary.
- Periodically review progress of ground-based program, and evaluate quality of final list. This includes a simulation of the expected contamination by binaries and companions which failed to be detected in the ground-based observations.
- Integrate models of residual grid star motion in the SIM Project's SIMSIM activity.
- Help PIs of narrow-angle observing programs identify their reference star needs (which may vary from program to program).
- Participate in analysis of global error budget, including instrumental and astrophysical error sources.
- Ensure communication between SIM Project, ISDC, and PIs about sources of errors and error budgets.
- Participate in on-orbit performance verification after launch.
- Work together with ISDC and SIM Project to identify problematic grid and reference stars early in the mission and propose substitutes or modifications to the affected observing program.
- Ensure continuity of grid star program and preserve knowledge over the whole mission lifetime.

These tasks require broad astronomical knowledge as well as thorough technical understanding of interferometry. Note that I am *not* proposing to develop algorithms or numerical techniques to perform the global astrometric solution incorporating all grid star observations. While a good understanding of this solution will be required for the tasks described above, I feel that others are better qualified to address the details of the required computations.

Skills and Experience of the PI that are Relevant to SIM

Experience in Optical / Infrared Interferometry

This proposal is submitted (somewhat arbitrarily) for a position of Data Scientist, because the description of this category most closely matches my current involvement in SIM. However, I have a long-standing interest both in interferometric techniques and in the analysis of interferometric data. I therefore expect that my role in the SIM Science Team would be somewhat intermediate between a Data Scientist and Instruments Scientist.

After obtaining a PhD in radio astronomy in 1990, I joined the optical interferometry group at the US Naval Research Laboratory and US Naval Observatory. During my three years there, I spent about 200 nights on Mt. Wilson observing with the Mk III interferometer, and thus gained hands-on instrument experience. During the observing runs I was responsible for the nightly operation of the interferometer, for baseline reconfigurations, alignment, maintenance, troubleshooting, and smaller repair work. However, most of my time was not devoted to technical tasks, but rather to making the Mk III scientifically productive. I took the lead in much of the Mk III work on "single stars". Astronomical results from this work include:

- Observations of asymmetries in the atmosphere of Mira (Quirrenbach et al. 1992).
- Measurements of angular diameters of carbon stars (Quirrenbach et al. 1994a).
- Direct measurements of limb darkening in Arcturus (Quirrenbach et al. 1996).
- Measurement of the angular diameter — and consequently of the distance — of Nova Cygni 1992 only ten days after maximum light (Quirrenbach et al. 1993a).
- Discovery of a substantial wavelength dependence across TiO bands of the diameter of late-type giants (Quirrenbach et al. 1993b).
- Proof that the circumstellar material in Be stars is organized in a thin disk, and measurements of the geometry of seven such disks (Quirrenbach et al. 1993c, 1994b, 1997).

I also participated in the Mark III programs on binary star orbits, wide-angle astrometry, and atmospheric characterization. In addition, I developed an algorithm to perform phase-referenced visibility averaging (Quirrenbach et al. 1994c); this technique increases the sensitivity for observations close to the first null of the visibility function.

From 1993 to 1997 I held a research scientist position at the Max-Planck-Institut für Extraterrestrische Physik in Garching, Germany. During this time I was very actively involved in the scientific and technical planning for the VLT Interferometer. I created the first concept of a mid-infrared instrument for the VLTI, pointed out that it would be a very powerful tool to address a number of outstanding questions both in galactic and extragalactic astronomy, and argued that it should be part of the first instrument complement. I presented these ideas at a meeting of ESO's Interferometry Science Advisory Committee, and then at the "Science with the VLTI" conference (Quirrenbach 1997); they evolved later into MIDI, which will be the first VLTI instrument. My second main contribution to the VLTI was the first proposal to implement an astrometric capability (Quirrenbach 1995), and the subsequent development of the PRIMA (Phase-Referenced Imaging and Microarcsecond Astrometry) concept (Quirrenbach et al. 1998). The main scientific driver for PRIMA is the search for extrasolar planets, the measurement of their masses, and the characterization of their orbits. In addition, PRIMA will allow imaging of faint objects, and can serve as an on-axis or off-axis fringe tracker. It will thus considerably enhance the capabilities of the other VLTI instruments including MIDI.

SIM and Grid Star Expertise

In 1997 I declined an offer to become head of ESO's interferometry project, and took a faculty position at UCSD. Shortly thereafter, I joined the SIM Science Working Group (SIMSWG) as a regularly invited guest. I participated in the SIMSWG meetings and in the writing of the Science Requirements Document. I quickly noticed that the grid star issue needed attention, and obtained a grant from the SIM Preparatory Science Program, with the goal to identify samples of potential grid stars from the Hipparcos and Tycho catalogs. Together with my postdoc Sabine Frink, whom I had hired for this project, I devised the approach of using distant K giants, and identifying binaries with radial velocities. We realized that photospheric variability would be a potential impediment for this strategy, and initiated the radial velocity survey of the proxy sample described above. This is a potentially very important contribution to SIM, as it could pave the way to a viable strategy to a "clean" set of grid stars. Just one year ago, no such strategy was known. It should be pointed out that we did not approach the grid star problem with a preconceived notion that one class of star or another would be the best solution. It was only after an initial impartial look at different possibilities that we deemed K giants the most promising. This is important because the selection of SIM grid and reference stars can only be successful if even-handed consideration is given to all potential approaches and their respective advantages and problems.

Long-Term Commitment to SIM and the SIM User Community

Interferometry has until recently been practiced almost exclusively by the instrument builders themselves. This has started to change with the planning for ground-based and space-based user facilities, such as ESO's VLTI, the Keck Interferometer, and SIM. Informing a broad community of potential users about the capabilities (and difficulties) of interferometry is therefore an important task, in which the SIM Science Team should adequately participate. I am very active in this area; I am particularly committed to educating graduate students and young researchers. I have been a member of the program committees for a number of international conferences, and I was Co-Chair (with P. Lena) of the SPIE conference *Interferometry in Optical Astronomy* (Munich, Germany, 2000). I gave a tutorial on Interferometry in Practice in conjunction with the conference *Science with the VLT Interferometer* (Garching, Germany, 1996). I was a lecturer at the NATO Advanced Study Institute *Laser Guide Star Adaptive Optics for Astronomy* (Cargèse, France, 1997) and at JPL's *Michelson Summer School* (Pasadena, CA, 1999); this year I will again give two presentations at the *Summer School on Space and Ground-Based Interferometry* (Leiden, The Netherlands, 2000). I am organizing the *CfAO / NOAO Summer School on Adaptive Optics* (Santa Cruz, CA, 2000). At the *Saas-Fee Advanced Course on Brown Dwarfs and Planets* I will give a series of nine lectures on detection and imaging of planets (Grimentz, Switzerland, 2001). I am currently writing a comprehensive review article on Optical and Infrared Interferometry for *Annual Review of Astronomy and Astrophysics* (2001). Through continuation of these and similar activities I will strive to contribute to the effective communication of the SIM Science Team with the astronomical community.

I intend to make a substantial contribution to the success of SIM, and I am prepared to commit a large fraction of my research effort to this goal. This is reflected in the budget, which includes a request for three months of my summer salary per year. I am also a member of a team proposing a Key Project (PI Geoff Marcy), with a similar commitment of my time. There is clearly overlap and synergism between my roles in these two proposals. Nonetheless, since the tasks are quite distinct, I will make proportionally more time available if both proposals are accepted. In that case I will use the SIM funding to "buy off time" from my regular teaching duties. The budget also requests long-term support for 50% of the salary for Dr. Sabine Frink. We propose to essentially fulfill a service function for SIM, which cannot easily be broken into thesis projects or research suitable for postdocs with short-term appointments. Therefore long-term support of a dedicated support scientist appears more appropriate than funding of a postdoc or graduate student.

I have spent a large fraction of my career doing optical and infrared interferometry, and participation in SIM is a logical continuation and extension of my main research interest. Since I hold a tenured position at a major research university I will be able to contribute to SIM continually over the whole lifetime of the mission. I look forward to meeting the challenges of space interferometry.

References

Bailyn, C.D.; Orosz, J.A., McClintock, J.E., Remillard, R.A., Nature 378, 157

Belloni, T, Dieters, S., van den Ancker, M.E., Fender, R.P., Fox, D.W., Harmon, B.A., van der Klis, M., Kommers, J.M., Lewin, W.H.G., van Paradijs, J., 1999, ApJ 527, 345

Boden, A., 1999, *SIM Astrometric Grid*, `http://sim.jpl.nasa.gov/library/technical_papers/sim_astro_grid1.pdf`

Boynton, P.E., Deeter, J.E., Lamb, F.K., Zylstra, G., 1986, ApJ 307, 545

Bradshaw, C.F., Fomalont, E.B., Geldzahler, B.J., 1999, ApJ 512, L121

Casares, J., Charles, P.A., 1994, MNRAS 271, L5

Cook, M.C., Page, C.G., 1987, MNRAS 225, 381

Fender, R.P., Garrington, S.T., McKay, D.J., Muxlow, T.W.B., Pooley, G.G., Spencer, R.E., Stirling, A.M., Waltman,E.B., 1999, MNRAS 304, 865

Frink, S., Quirrenbach, A., Röser, S., Schilbach, E., 2000a, in *Working on the fringe*, eds. S. Unwin, & R. Stachnik, ASP Conference Series Vol. 194, p. 128

Frink, S., Quirrenbach, A., Fischer, D., Röser, S., Schilbach, E., 2000b, in *Interferometry in Optical Astronomy*, eds. P. Lena & A. Quirrenbach, SPIE Vol. 4006, in press

Gies, D.R., Bolton, C.T., 1986, ApJ 304, 371

Greiner, J., Predehl, P., Pohl, M., 1995, A&A, 297, L67

Herrero, A., Kudritzki, R.P., Gabler, R., Vilchez, J.M., Gabler, A., 1995, A&A 297, 556

Hjellming, R.M., Rupen, M.P., 1995, Nature 375, 464

Hummel, C.A., Armstrong, J.T., Buscher, D.F., Mozurkewich, D., Quirrenbach, A., Vivekanand, M., 1995, AJ 110, 376

Iye, M., 1986, PASJ 38, 463

Jacobs, C., Turyshev, S., 1999, AAS 195, 46.12

Lena, P., Quirrenbach, A. (Editors), 2000, *Interferometry in Optical Astronomy*, SPIE Vol. 4006, in press

Makishima, K., Kawai, N., Koyama, K., Shibazaki, N., Nagase, F., Nakagawa, M., 1984, PASJ 36, 679

Margon, B., Anderson, S.F., 1989, ApJ 347, 448

Margon, B., Bowyer, S., Stone, R.P.S., 1973, ApJ 185, L113

Mason, B.D., Hajian, A.R., Urban, S.E., 1999, AAS 195, 46.04

Miller, J.C., Shahbaz, T., Nolan, L.A., 1998, MNRAS 294, L25

Mirabel, I.F, Rodriguez, L.F., 1994, Nature 371, 46

Nagase, F., 1989, PASJ 41, 1

NASA, 1999, *SIM Interferometry Mission: Taking the Measure of the Universe*, eds. R. Danner & S. Unwin, JPL 400-811

Ninkov, Z., Walker, G.A.H., Yang, S., 1987, ApJ 321, 425

Oda, M., Gorenstein, P., Gursky, H., Kellogg, E., Schreier, E., Tananbaum, H., Giacconi, R., 1971, ApJ 166, L1

Orosz, J.A., Bailyn, C.D., 1997, ApJ 477, 876

Patterson, R.J., Majewski, S.R., Kundu, A., Kunkel, W.E., Johnston, K.V., Geisler, D.P., Gieren, W., Muñoz, R., 1999, AAS 195, 46.03

Phillips, S.N., Shahbaz, T., Podsiadlowski, Ph., 1999, MNRAS 304, 839

Predehl, P., Schmitt J.H.M.M., 1995, A&A 293, 889

Quirrenbach, A., 1995, in *Science with the VLT*, eds. J.R. Walsh, & I.J. Danziger, Springer-Verlag, p. 33

Quirrenbach, A., 1997, in *Science with the VLT Interferometer*, ed. F. Paresce, Springer-Verlag, p. 385

Quirrenbach, A., Mozurkewich, D., Armstrong, J.T., Johnston, K.J., Colavita, M.M., Shao, M., 1992, A&A 259, L19

Quirrenbach, A., Elias, N.M., Mozurkewich, D., Armstrong, J.T., Buscher, D.F., Hummel, C.A., 1993a, AJ 106, 1118

Quirrenbach, A., Mozurkewich, D., Armstrong, J.T., Buscher, D.F., Hummel, C.A., 1993b, ApJ 406, 215

Quirrenbach, A., Hummel, C.A., Buscher, D.F., Armstrong, J.T., Mozurkewich, D., Elias, N.M., 1993c, ApJ 416, L25

Quirrenbach, A., Mozurkewich, D., Hummel, C.A., Buscher, D.F., Armstrong, J.T., 1994a, A&A 285, 541

Quirrenbach, A., Buscher, D.F., Mozurkewich, D., Hummel, C.A., Armstrong, J.T., 1994b, A&A 283, L13

Quirrenbach, A., Mozurkewich, D., Buscher, D.F., Hummel, C.A., Armstrong, J.T., 1994c, A&A 286, 1019

Quirrenbach, A., Mozurkewich, D., Buscher, D.F., Hummel, C.A., Armstrong, J.T., 1996, A&A 312, 160

Quirrenbach, A., Bjorkman, K.S., Bjorkman, J.E., Hummel, C.A., Buscher, D.F., Armstrong, J.T., Mozurkewich, D., Elias, N.M., Babler, B.L., 1997, ApJ 479, 477

Quirrenbach, A., Coudé du Foresto, V., Daigne, G., Hofmann, K.-H., Hofmann, R., Lattanzi, M., Osterbart, R., le Poole, R., Queloz, D., Vakili, F., 1998, in *Astronomical Interferometry*, SPIE Vol. 3350, p. 807

Remillard et al., 1999, ApJ 522, 397

Rhoades, C.E., Ruffini, R., 1974, PRL 32, 324

Shapiro, S.L., Teukolsky, S.A., 1983, *Black Holes, White Dwarfs and Neutron Stars*, John Wiley and Sons

Soria, R., Wickramasinghe, D.T., Hunstead, R.W., Wu, K., 1998, ApJ 495, L95

Stickland, D., Lloyd, C., Radziun-Woodham, A., 1997, MNRAS 286, L21

Toscano, M., Sandhu, J.S., Bailes, M., Manchester, R.N., Britton, M.C., Kulkarni, S.R., Anderson, S.B., Stappers, B.W., 1999, MNRAS 307, 925

Urban, S., Mason, B., Horch, E., Holdenried, E., Rafferty, T., Hartkopf, W., van Altena, W., 1999, AAS 195, 46.07

van der Hooft, F., Groot, P.J., Shahbaz, T., Augusteijn, T., Casares, J., Dieters, S., Greenhill, J., Hill, K., Scheers, L.H.A., Naber, R.M., de Jong, J.A., Charles, P.A., van Paradijs, J., 1997, MNRAS 286, L43

van der Klis, M., Bonnet-Bidaud, J.M., 1984, A&A 135, 155

van Kerkwijk, M.H., van Paradijs, J., Zuiderwijk, E.J., Hammerschlag-Hensberge, G., Kaper, L., Sterken, C., 1995a, A&A 303, 483

van Kerkwijk, M.H., van Paradijs, J., Zuiderwijk, E.J., 1995b, A&A 303, 497

van Paradijs, J., White, N.E., 1995, ApJ 447, L33

Wade, R.A., 1999, AAS 195, 46.06

Walker, G.A.H., Walker, A.R., Irwin, A.W., Larson, A.M., Yang, S.L.S., Richardson, D.C., 1995, Icarus 116, 359

White, N.E., Nagase, F., Parmar, A.N., 1995, in: *X-ray Binaries*, eds. H.G. Lewin, J. van Paradijs, E.P.J. van den Heuvel, Cambridge Astrophysics Series, p. 1

White, N.E., van Paradijs, J., 1996, ApJ 473, L25

Wijnands, R., van der Klis, M., 2000, ApJ 528, L93

Zhang, S.N., Wilson, C.A., Harmon, B.A., Fishman, G.J., Wilson, R.B., Paciesas, W.S., Scott, M., Rubin, B.C., 1994, IAUC 6046

Zhang, S.N., Cui, W., Chen, W., 1997, ApJ 482, L155