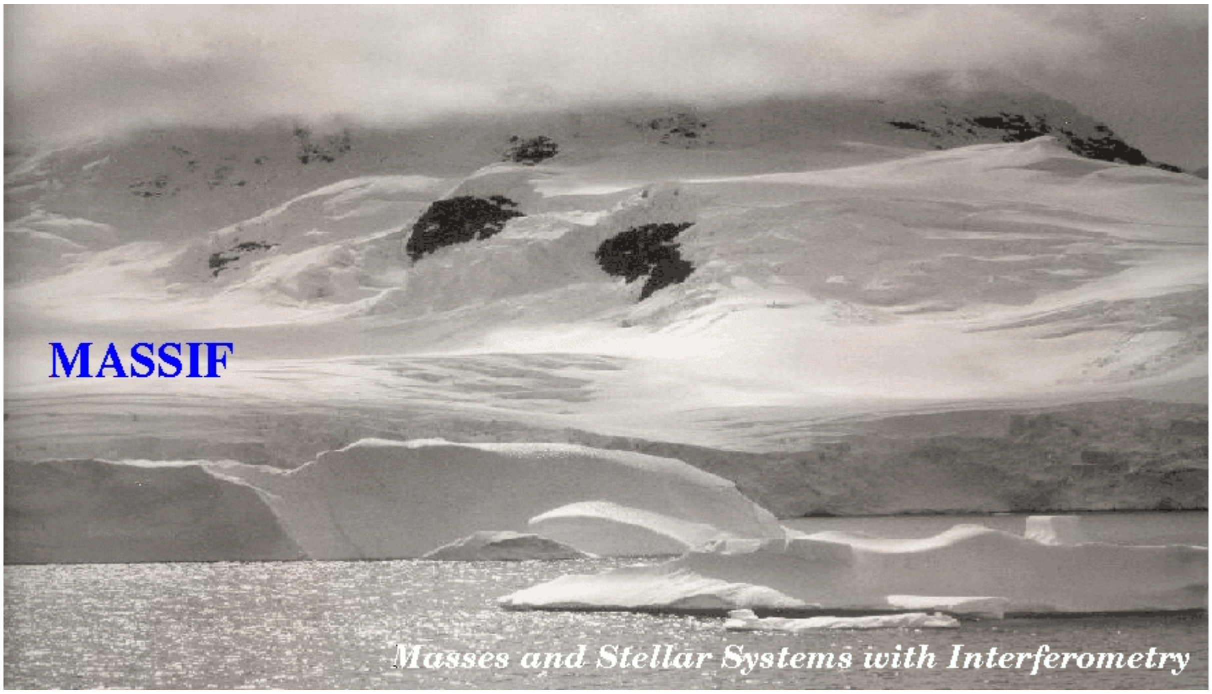

A MASSIF EFFORT TO DETERMINE THE MASS-LUMINOSITY RELATION FOR STARS OF VARIOUS AGES, METALLICITIES, AND EVOLUTIONARY STATES

Todd J. Henry
(Georgia State University beginning August 2000)

G. Fritz Benedict
McDonald Observatory, Austin, TX 78712

Douglas R. Gies
Georgia State University, Atlanta, GA 30303

David A. Golimowski
Johns Hopkins University, Baltimore, MD 21218

Philip A. Ianna
University of Virginia, Charlottesville, VA 22903

Brian D. Mason
United States Naval Observatory, Washington, DC 20392

Barbara E. McArthur
McDonald Observatory, Austin, TX 78712

Edmund P. Nelan
Space Telescope Science Institute, Baltimore, MD 21218

Guillermo Torres
Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138

The MASSIF (Masses and Stellar Systems with Interferometry) Team will investigate the mass content of the Galaxy — from huge stars to barely glimmering brown dwarfs, and from hot white dwarfs to exotic black holes. We will target various samples of the Galactic population to determine and relate the fundamental characteristics of mass, luminosity, age, composition, and multiplicity — attributes that together yield an extensive understanding of the stars. Our samples will include distant clusters that span a factor of 5000 in age, and commonplace stars and substellar objects that lurk near the Sun.

Mass is the most fundamental characteristic of a star. It is crucial to our understanding of stellar astrophysics that we determine stellar masses to high accuracy. The principal goals of the MASSIF Key Project are (1) to define the mass-luminosity relation for main sequence stars in five clusters so that effects of age and metallicity can be mapped, and (2) to determine accurate masses for representative examples of nearly every type of star, stellar descendant, or brown dwarf in the Galaxy. To reach these goals we will measure masses with errors of 1% or less for roughly 200 stars, which will allow us to challenge stellar astrophysics models more severely than ever before. There are currently only ~40 stars with masses this accurately known, and 30 of those are components in eclipsing binaries with masses between 1 and 3 $M_\odot$. Thus, the range of our understanding of precise stellar masses is terribly limited. SIM can rectify this situation because it has the capability to measure precisely the largest known mass for a star, as well as the smallest known mass for a brown dwarf. The extrema of the H-R Diagram will receive intense scrutiny so that we can understand just where the stellar main sequence begins and ends. We will also investigate exotic targets such as supergiants and black holes to further our understanding of these rare but intriguing objects. In the process of carrying out this investigation, we will develop a well-stocked "toolbox" of mass-luminosity relations at optical and infrared wavelengths that can become the standards against which all stars are measured.

The MASSIF Team will provide the SIM Project a list of targets that have been well-calibrated using various ground-based techniques. In some cases, the targets will allow the Project to check independently SIM's ability to measure orbits, brightness ratios, and parallaxes. An important consequence of our program will be accurate masses for stars that have extrasolar planets. SIM will not "see" planets — it will only measure the effects that planets have on their host stars. Even when combined with high-precision radial velocity data, an estimate of the star's mass is required to derive the mass of the planet. Our ensemble of mass-luminosity relations will allow accurate estimates for the masses of stars with extrasolar planets, and consequently, accurate estimates for the planet masses. Finally, the proposed observations of a variety of stellar binaries would provide simple, yet superb, test cases for the imaging and nulling capabilities of SIM.

The resources requested will be divided among our team experts at seven different institutions. This benefits the SIM Project because connections to students and the public can be made at each location, and because many affiliated observatories will support the proposed SIM science. Resources are concentrated at locations where much of the target selection work will be done, but each investigator has been allocated sufficient funding to get the job done. In total, we request ∼\$500K/year.

One of the great strengths of the MASSIF effort is our team. Regarding stellar and substellar masses, our team has unrivaled expertise in knowing what astrophysical questions need to be answered, what targets must be investigated to answer them, and how we must carry out observations to obtain meaningful results. Since 1990, members of the MASSIF team have published over 50 papers on stellar masses in the refereed literature, and we have a rich history of cooperation and collaboration. We are familiar with every aspect of target selection — from characterization of stars in clusters and the field to careful identification of the few targets that will yield the best scientific results. We have experts on every type of star for which masses might be determined. Gies and Nelan are experts in the massive OB stars and the Trapezium. Golimowski, Henry, and Ianna are recognized as leaders in the field of low-mass stars and brown dwarfs. Mason and Torres are well known for their deep understanding of solar-type stars in the Hyades, Pleiades, and M67. The MASSIF Team knows exactly what data will be needed for successful determination of masses with SIM, how that data must be obtained, reduced, and combined. Our team is fortunate to include Benedict and Ianna, whose experience in astrometry spans decades. Moreover, our team (in particular, Gies, McArthur and Torres) has a rigorous understanding of the methodology required to combine spectroscopic, astrometric, visual, speckle, and interferometric data, and knows how to extract the most information from these data. The depth of our team's experience in high-resolution techniques cannot be overstated. We have a wealth of experience using optical/infrared speckle interferometry, adaptive optics, and of particular relevance to SIM, space interferometry with the Fine Guidance Sensors on HST. Finally, we have demonstrated expertise in developing mass-luminosity relations. Our efforts are recognized as benchmarks for both nearby field stars (Henry) and the Hyades (Torres), the only two environments in which empirical mass-luminosity relations have been determined.

The MASSIF Team has access to state-of-the-art observing facilities that will be needed for both target selection and observations complementary to SIM. These facilities include the long-baseline CHARA Array (Gies, Henry) for interferometry, the Hobby Eberly Telescope (Benedict, McArthur) and the CfA telescopes including the newly converted MMT (Torres) for radial velocity measurements, the USNO Speckle Camera (Mason) for target characterization, and the Sloan Digital Sky Survey (Golimowski), and southern parallax programs in Australia (Ianna) and Chile (Henry, Ianna) for target discovery.

Finally, our team has a passion for outreach activities that will benefit the SIM Project. Benedict's popular Shapley lectures span more than a decade. Gies and Ianna have been working in public schools and coordinating public nights in Georgia and Virginia for a similar time. Henry has worked with the media, both in print and film format, to bring accurate scientific results to the public.

Simply put, when it comes to determining masses for objects in the Galaxy, the MASSIF Team is up to the challenge.

2.1. Science Objectives

Mass is the most fundamental characteristic of a star. It governs a star's entire evolution — determining which fuels it will burn, what color it will be, and how long it will live. Knowing the masses of main sequence stars answers basic stellar astrophysics questions such as, What is the biggest star? How is the mass of a stellar nursery partitioned into various types of stars? and, What is the mass content of the Galaxy and how does it evolve? The public is keenly interested in stars because stars are the astronomical objects that can be pointed to in the night sky. It is therefore important for astronomers to know the masses of stars not only for astrophysical reasons, but so we can convey this information to any student, friend, or acquaintance who might ask about the stars.

The mass of a given star is difficult to determine, but its luminosity is not. To determine the latter, only a star's brightness and distance must be known. However, simply determining a star's luminosity does not provide a good handle on its mass because the relation between luminosity and mass depends upon the star's age and metallicity. For most classes of stars, the mass can be estimated to 15–20% at best. This is insufficient to know precisely what type of star is being considered, and woefully inadequate for critical tests of stellar models, which require accuracies of $\sim$1% (Andersen 1991, 1998).

The dependence of luminosity upon mass — the mass-luminosity relation (MLR) — is one of the few stellar relations sufficiently fundamental to be applicable to many areas of astronomy. With the exception of the H-R Diagram, it is the single most important "map" of stellar astronomy. For single objects, the MLR allows astronomers to convert a relatively easily observed quantity, luminosity, to a more revealing characteristic, mass, that yields a better understanding of the object's nature. In searches for extrasolar planets, the MLR provides masses for the target primary stars and consequently allows us to derive the unseen companion's mass. In the broader context of the Galaxy, an accurate MLR permits a luminosity function to be converted to a mass function, and drives estimates of the stellar contribution to the Galactic mass.

Despite its broad utility, the MLR remains poorly defined for many regions of the H-R Diagram. Figure 1 (Henry & Torres 2000) shows that over most of the main sequence there is nearly a factor of two uncertainty for a mass if the luminosity ($M_V$in this case) is known, e.g. at $M_V = 0$, the mass estimates are 2.5–4.0 $M_\odot$; at $M_V = 5$, 0.8–1.4 $M_\odot$; at $M_V = 10$, 0.28–0.6 $M_\odot$; at $M_V = 15$, 0.12–0.22 $M_\odot$. The extrema of the main sequence are where the MLR needs rigorous investigation. At present, only a few masses are known for stars on the upper ($M > 20$ $M_\odot$) and lower ($M < 0.20$ $M_\odot$) main sequence, and these masses typically have errors in excess of 10% (Harries *et al* 1998; Henry *et al* 1999). For a truly meaningful investigation of the effects of age and metallicity, the accuracy of masses must be better than 1%. Of the $\sim$40 stars with masses this accurately known (all in eclipsing binaries), three-quarters have masses between 1 and 3 $M_\odot$. This is a terribly limited range over which to test stellar models. Another example of why the MLR must be improved is evident in Figure 1: at masses below 0.8 $M_\odot$ only one of the three eclipsing binaries known falls on the empirical MLR of Henry & McCarthy (1993). Clearly, efforts to disentangle the relations between mass, luminosity, age and metallicity have barely begun.

We have unified efforts under the team name MASSIF (Masses and Stellar Systems with Interferometry) to attack the basic problem of accurate stellar masses. The acronym is aptly chosen (a massif is a principal mountain mass that dominates a landscape) because the mission of MASSIF is to explore the entire range of stellar masses in the Galaxy, from the flashy O stars to the ubiquitous red and brown dwarfs. Our team is ideally suited to carry out this project because since 1990 we have collectively published 56 refereed papers that report binary orbits and/or masses (see §8). Moreover, the MASSIF Team has several dozen papers that report parallaxes for nearby stars and searches for companions to stars spanning the entire main sequence. We plan to observe these very targets with SIM.

The MASSIF Team will (1) determine MLRs for a range of clusters with known ages and metallicities, and (2) determine masses and luminosities of field stars and compare them to the cluster MLRs. Open clusters are excellent laboratories for the study of stellar astrophysics because they provide large numbers of stars with the same age and chemical composition. Mapping an ensemble of clusters to a grid of compositions, ages and kinematics will lead to a greater understanding of star formation, chemical evolution, and abundance gradients in the Galaxy. To date, the only cluster for which an MLR has been determined is the Hyades (Torres *et al* 1997c). However, the Hyades MLR extends only from 2.4 to 0.8 $M_\odot$ with mass errors of 5–10%. This MLR is insufficient for critical tests of the models and does not include the smallest stars for which the age and metallicity effects are most pronounced. SIM's great accuracy is needed to reduce these errors to the 1% level needed for meaningful analysis.

To lay a solid foundation for stellar astronomy, the MASSIF Team has developed the following list of goals achievable with SIM. We will:

1. Use SIM to define the MLR for main sequence stars by observing a suite of carefully selected clusters for which ages and metallicities are known. These clusters have ages spanning a factor of 5000, from 1 Myr to 5 Gyr.

2. Challenge stellar astrophysics models by obtaining masses and luminosities accurate to 1%.

3. Provide a "toolbox" full of MLRs at $UBVRIJHK$ wavelengths as a function of age and metallicity.

4. Map out the extrema of the MLR by measuring masses of the largest OB stars and the smallest red and brown dwarfs. This investigation will answer the fundamental question, What are the maximum and minimum masses for a star?

5. Determine masses for exotic objects such as supergiants, white dwarfs, and black holes. When combined with SIM observations of OB stars, we will illuminate the properties of the massive stars from birth to death.

6. Evaluate and compare the multiplicity fractions and structures in five key clusters. Preparatory work will result in radial velocities for cluster members and an accurate census of binaries in each cluster. When combined with SIM proper motions and parallaxes, the target binaries will have accurate space motions, and we can make first steps toward three-dimensional dynamic maps of each cluster.

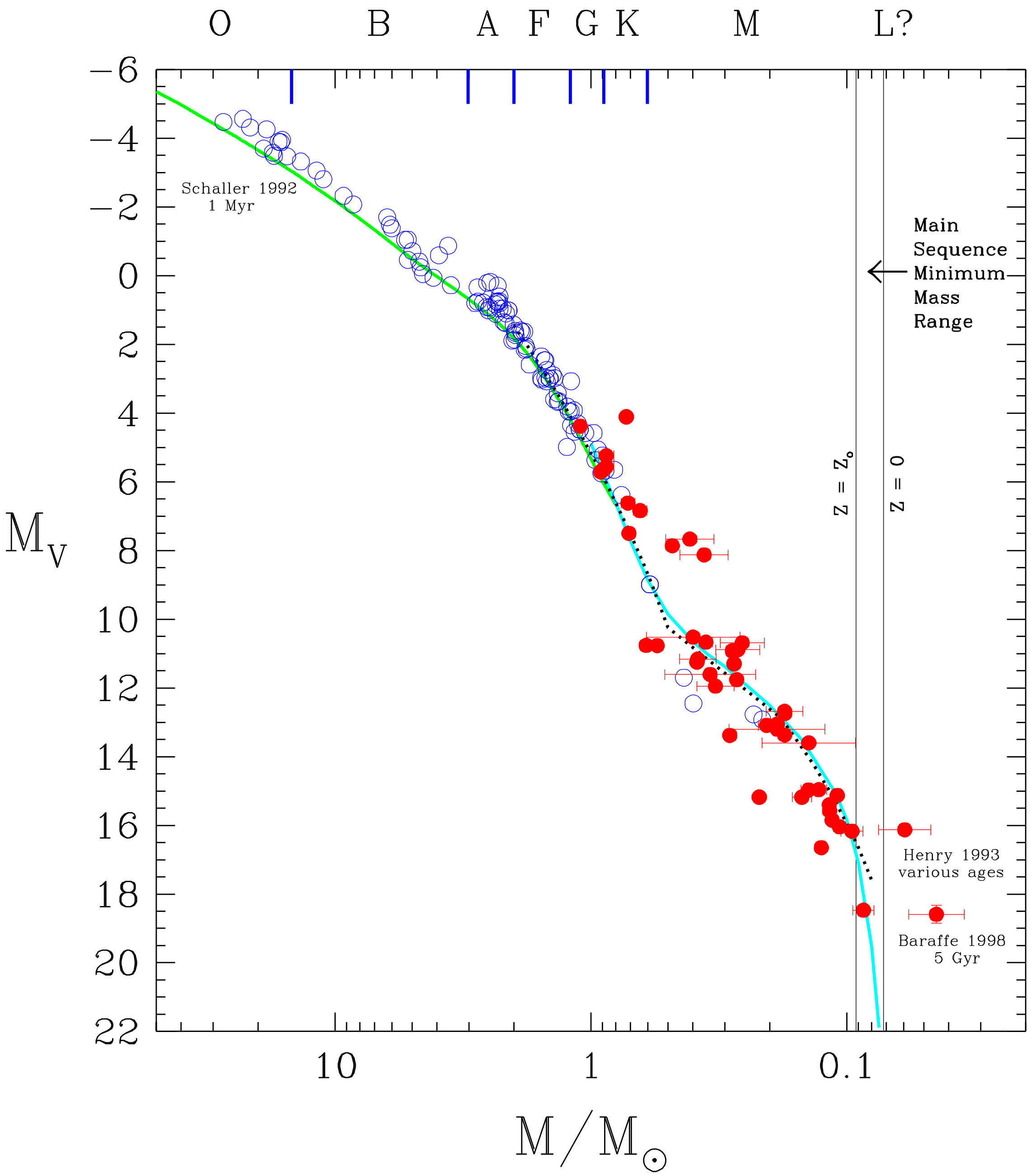

Figure 1: The Mass-Luminosity Relation at optical wavelengths for field stars is shown (Henry & Torres 2000). Masses from 30 $M_\odot$ to 0.08 $M_\odot$ are represented by open points for eclipsing binaries and solid points for astrometric binaries. The region from 0.092 and 0.072 $M_\odot$ marks the minimum main sequence mass range for objects with zero to solar metallicity. Three fits are shown — model fits for massive stars from Schaller *et al* (1992) and for low mass stars from Baraffe *et al* (1998), and empirical fits (dotted line) from Henry & McCarthy (1993) and Henry *et al* (1999). Each fit has a terminus near 1 $M_\odot$.

In addition to contributing fundamental science, the MASSIF Key Project will benefit the overall SIM Project because it will:

1. Provide a list of targets that have been well-calibrated using various ground-based techniques. Some of the targets will allow independent checks of the parallaxes, orbits, and brightness ratios obtained with SIM. For example, SIM parallaxes can be directly calibrated against the orbital parallax of an SB2 system that has been resolved with other techniques, such as the CHARA Array.

2. Calibrate the masses of stars around which planets are found using MASSIF's grid of MLRs. SIM will not "see" planets, but will measure their effects on the host stars. Even when astrometric and radial velocity orbits are combined, the mass of the star must be assumed to determine the mass of the planet.

3. Provide simple, excellent test sources for imaging and nulling capabilities.

One of the clear strengths of this proposal is that it has a guaranteed payoff. Binary stars *will* be resolved, orbits *will* be mapped, mass-luminosity relations *will* be forthcoming. This is not a fishing expedition — this is guaranteed high level astrophysics. We will greatly advance our understanding of stellar structure and evolution because many aspects have not yet been seriously challenged with observations. In addition to mapping the complicated interplay between mass, luminosity, age, and metallicity, we will explore the convection prescriptions (including overshooting) for moderately evolved stars, compare the helium content of clusters, evaluate the opacities for relatively unevolved systems, and gain a further understanding of mass loss rates in early-type stars.

2.2. Science Targets

SIM's exquisite accuracy comes with a price — only a limited number of targets can be observed. To achieve the 1% mass error required to reach our goals, significant effort must be devoted to careful selection and characterization of target stars. The MASSIF Team has the experience and capabilities needed to perform these tasks effectively and expeditiously.

Our ambitious goal is to determine masses for 10–20 objects in each of the 10 categories described below and listed in Table 1. All of the Cluster Sample targets and most of the Special Sample targets will be double-lined spectroscopic binaries (SB2s) having periods of 5 years or less. The SB2 criterion provides a nearly complete orbit (the inclination remains unknown) that when combined with SIM measurements will yield accurate masses. The 5 year criterion is set by SIM's lifetime, during which a complete orbit can be observed. An evaluation of the 228 stellar systems known within 10 pc of the Sun indicates that finding suitable targets should not be a problem. In this sample, there are 164 singles, 46 doubles, 13 triples, 4 quadruples and 1 quintuple — 316 objects in all (Henry 2000). Thus, at least 28% of the nearby systems are multiple. In total, 23 of the 228 systems have periods less than 5 years, meaning that 10% or more of nearby systems are suitable for the MASSIF Key Project. Assuming that the clusters' multiplicities are similar to that of nearby stars (the multiplicity fractions of the field and Trapezium stars are indistinguishable; Petr *et al* 1998), we should have no problem identifying suitable targets in the clusters.

For the five clusters, our minimum objective is to determine points on the MLR covering an order of magnitude in mass. Selected cluster binaries will have mass ratios of 0.4–0.9, which is advantageous because (1) the magnitude differences are not large, which is ideal for both imaging and radial-velocity measurements, (2) the photocentric orbits are sizeable (equal mass systems have near-zero magnitude differences and present little or no photocentric orbit), and (3) there will be no source confusion.

The scientific products from SIM will be parallaxes, proper motions, and orbits (absolute or photocentric) for each of the 100 systems targeted. These products will not only allow us to determine precise masses and luminosities, but also enable us to measure the depths of clusters. Thus, we will develop three-dimensional pictures of the five clusters, as well as map the motions of the stars within the clusters. Comparative studies of these clusters may reveal anomalous attributes that could explain the star formation history of each.

Table 1. *Samples Targeted in MASSIF Effort*

Sample	Age	Distance	[Fe/H]	# objects known in cluster	# objects with mass errors <5%	# objects with mass errors <1%	# objects our goal
Trapezium	1 Myr	450 pc	−0.12	500	0	0	20
TW Hydrae	10 Myr	50 pc	∼0	23 to date	0	0	20*
Pleiades	120 Myr	110 pc	−0.03	500	0	0	20
Hyades	600 Myr	45 pc	+0.13	400	2	2	20
M67	4-5 Gyr	800 pc	+0.02	>500	0	0	20
OB Stars	<5 Myr	>1000 pc	various	—	9	0	10
White Dwarfs	various	< 20 pc	various	—	1	0	10
Red Dwarfs	various	< 20 pc	various	—	20**	4	10
Brown Dwarfs	various	< 50 pc	various	—	0	0	10
Exotics	various	various	various	—	—	—	10

* Tentative, subject to discovery of more members. ** More than half determined by members of the MASSIF Team.

We now outline the five clusters and five special samples that constitute the core of the MASSIF Key Project. These are presented in Table 1, for which we have taken results from Boesgaard & Friel (1990), Cunha *et al* (1995), Friel & Boesgaard (1992), Stauffer (1996), and Webb *et al* (1999). *We stress that the cluster samples and special samples listed in the following sections are exemplary, not exhaustive.* The MASSIF Team is committed to determining representative masses for *every* class of star, stellar descendant, or brown dwarf in the Galaxy. We expect to add or substitute other clusters or special samples of objects if those targets are astrophysically compelling.

2.2.1. CLUSTER 1: Trapezium — 1 Myr Old

The Trapezium Cluster in Orion is a very young (< 2 Myr; Palla & Stahler 1999), nearby (450 pc) open cluster containing many massive stars. It is an excellent benchmark for very young star astrophysics. Most objects with masses below 8 $M_\odot$ are in the pre-main sequence phase, so they are easier to detect than their main sequence counterparts. Preliminary high angular resolution surveys of the Trapezium reveal the presence of many binary stars (Preibisch *et al* 1999; Petr *et al* 1998), several of which will allow accurate mass determinations. One companion to θ^1 Ori C has been resolved with a separation of 33 mas (Weigelt *et al* 1999), which corresponds to a projected separation of 15 AU and a probable period of 11 years. Two of the four Trapezium stars are spectroscopic binaries (Abt *et al* 1991). These stars, θ^1 Ori A (SB1) and θ^1 Ori B (SB2), are also eclipsing binaries with periods of 65 and 6.5 days, respectively. Their masses, however, are only known to within a factor of two because obtaining precise velocities is difficult for such massive stars. Their estimated mass ratios indicate that the stars should exhibit reflex motions of ~0.70 and ~0.13 mas, respectively. Two other stars, θ^2 Ori (O9) and HD 37061 (B1V) are SB1s with periods of ~20 days. Their mass ratios of ~0.3 suggest reflex motions of ~0.27 mas. SIM will easily measure the photocentric orbits for all five systems.

We will work to reveal massive ($M > 10\ M_\odot$) binary stars in Orion with periods of up to ~ 5 years. These systems will have separations of ~ 5–8 AU (or ~ 10–17 mas), which, along with the θ^1 Ori C system, will be easily resolved by the CHARA Array. CHARA's map of the relative orbits will allow us to avoid the problems associated with inadequate precision in radial velocity studies and SB1 systems. SIM will complement the CHARA observations by mapping the photocentric orbit, and combining the photocentric and relative orbits will yield highly accurate masses for both components.

2.2.2. CLUSTER 2: The TW Hydrae Association — 10 Myr Old

Approximately 10 Myr old and ~50 pc distant, the recently identified TW Hydrae association (TWA) is the closest cluster of its age to Earth. Uncommonly isolated from any known progenitor molecular clouds, TWA bridges the age gap between 1 Myr-old T Tauri stars that lie in clouds and ~30 Myr-old open clusters like IC 2602 and IC 2391. There are already 23 probable members in TWA (Webb *et al* 1999), comprising 3 singles, 5 doubles, 2 triples and a quadruple. The companion to one close binary system, CD −33°7795, is probably substellar. Because of its proximity and recent star formation, TWA is an excellent target for seeking and studying the MLR for bright brown dwarfs.

The quadruple in TWA is HD 98800, a post T-Tauri star that is famous for its extreme infrared excess (Soderblom *et al* 1998a). Each of the visible K stars is a close spectroscopic binary, with periods of 262 and 315 days for the AC and BD components, respectively (Torres *et al* 1995). The BD binary provides an ideal opportunity to determine the relation between mass and luminosity for objects with an age of 10 Myr because of its modest brightness difference and SB2 orbit. Given approximate masses of 0.8 and 0.5 $M_\odot$, the predicted semimajor axis of the system is 21 mas, easily resolvable with SIM. An accurate parallax and semimajor axis will produce mass errors of only 0.1%. The current best estimates of the masses have errors of more than 40%.

2.2.3. CLUSTER 3: The Pleiades — 100 Myr Old

The Pleiades is a young (~120 Myr old), nearby (~110 pc) open cluster of stars with solar metallicity. *Hipparcos* measurements of the Pleiades have clouded our understanding of the properties of stars that have recently arrived on the main sequence because the *Hipparcos* distance modulus for the Pleiades (5.35) is 0.3 mag less than that expected from model fits of the cluster's main sequence. This discrepancy cannot be attributed to the published uncertainty of the measured parallax (8.63 ± 0.24 mas; van Leeuwen & Hansen Ruiz 1997).

This result suggests two unsettling possibilities: zero-age main sequence (ZAMS) stars are 30% fainter than established theory predicts, or the *Hipparcos* measurements of the Pleiades are flawed.

SIM will measure the distance to the Pleiades with an accuracy 60 times better than that of *Hipparcos*. Thus, SIM will not only resolve the dilemma regarding Pleiades luminosities, but also impose strict constraints on ZAMS astrophysics. With a limiting magnitude of $V = 20$, SIM will be sensitive to Pleiads with masses greater than 0.1 $M_\odot$, corresponding to spectral types as late as M5. At least nine SB2s have already been identified in the Pleiades (Abt *et al* 1965; Mermilliod *et al* 1992; Soderblom *et al* 1993; Giannuzzi 1995; Soderblom 1998b). Of these, HII 173, a K0V SB2 with a period of 480 days, has a semimajor axis of $\sim$13.0 mas. SIM will be able to measure both orbits of this binary pair, and hence the component masses, to better than 0.2%.

2.2.4. CLUSTER 4: The Hyades — 600 Myr Old

The Hyades open cluster lies only 45 pc away and has a metallicity slightly higher than that of the Sun. Of the five binary systems in the Hyades with directly determined masses, only one (a double-lined eclipsing binary) has a mass better than 1%. The other four are astrometric-spectroscopic binaries with mass errors of 5–15%. Nonetheless, this is the only cluster in which a MLR (currently spanning 0.8–2.4 $M_\odot$) of any kind has been determined (Torres *et al* 1997c).

SIM's astrometric accuracy will be orders of magnitude better than that of visual or speckle astrometry, which have been used to determine the orbital inclinations. As an example of the gains to be made in the Hyades, we examine the binary θ^2 Tau. As presented in Torres *et al* (1997c), the binary's period is 140.7 days with negligible error. The semimajor axis is 18.6 ± 0.2 mas and the mass errors are 12%, primarily due to errors in the semimajor axis and fractional mass. SIM can improve both quantities substantially because the large semimajor axis will allow the orbits of both stars to be mapped relative to the grid stars. Assuming errors of 0.04 mas (or 10 times the nominal astrometric accuracy of SIM for Global Astrometry) in the semimajor axis and parallax (current error 0.8 mas), and the fractional mass to a comparable relative precision (0.2%), the mass errors determined by SIM alone would be only 0.9%, a factor of 80 improvement.

2.2.5. CLUSTER 5: M67 — 5 Gyr Old

The open cluster M67 (NGC 2682) contains over 500 known members with spectral types B9–K4 and brightnesses $10 < V < 16$. The turnoff of M67's MLR suggests that the cluster is about as old as the Sun. M67 provides a unique laboratory in which to evaluate mass segregation from dynamical relaxation, as has been clearly shown by Mathieu & Latham (1986). By precisely measuring the distances to stars of various masses in M67, SIM will allow us to determine directly the mass distribution, and test models of relaxed mass distributions. As a bonus to the determination of the MLR in M67, its distance would be improved from the current 10% accuracy offered by *Hipparcos* to only 0.3%.

Assuming a 38% multiplicity fraction for M67 (Montgomery *et al* 1993), the cluster offers a large sample of binary stars spanning a wide range of spectral types from which to choose appropriate SIM targets. As an example, the SB2 binary S999 is composed of stars of brightness $V = 13.0$ and 14.0, in an orbit with a period of 10 days (Mathieu *et al* 1990). The photocentric orbit's semimajor axis of 28 μas is well within reach of SIM. The inclination from this orbit combined with the spectroscopy will easily yield masses better than 1%.

2.2.6. SPECIAL SAMPLE 1: O and B Stars

Massive stars are key contributors to the energy budget and chemical enrichment of the Galaxy, but little is presently known about their masses. There are only five known eclipsing binaries among the O stars that have reasonably well established masses (Harries *et al* 1998), and this lack of data has seriously hindered our understanding of the evolution of massive stars. One unknown, for example, is the maximum mass possible for a star. Interior models for massive stars predict that stable stars can exist with initial masses of 120 $M_\odot$, but the most massive object among the five eclipsing binaries is only $33 M_\odot$. Furthermore, indirect methods of estimating mass by comparison with model evolutionary tracks and through spectroscopic diagnostics lead to discrepancies as large as a factor of two (Herrero *et al* 2000). SIM will record the photocentric and/or absolute orbits of many binaries and by combining this information with spectroscopic data it will be possible to determine accurate distances, inclinations, and masses. An excellent example is the massive binary, HD 93205, which consists of an O3V + O8V pair in a 6.08 day orbit. SIM observations will show a 45 μas photocentric variation that will yield the first accurate mass for a star at the top of the main sequence (only known to be in the range of 32–154 $M_\odot$; Antokhina *et al* 2000).

SIM will also provide the first accurate masses of the evolutionary descendants of massive stars. The most massive stars develop strong outflows later in life and appear as Wolf-Rayet (WR) stars. SIM measurements of the WR binary, WR 22 (WN7 + O9III; Schweickhardt *et al* 1999), will show a 250 μas astrometric variation through the 80.3 day orbit, and these measurements will provide the mass of this extraordinary object (currently estimated to be 55 ± 7 $M_\odot$, the most massive star known). Intermediate-mass B stars in close binaries are believed to suffer extensive mass transfer and mass loss during the Roche lobe overflow phase. The best example of this evolutionary stage is the enigmatic binary, η Lyr (Bisikalo *et al* 2000), which consists of a bright, 3 $M_\odot$ star losing mass to a 13 $M_\odot$ gainer hidden in an extensive accretion disk. The astrometric orbital motion of the bright component will amount to 820 μas, and SIM will provide accurate mass estimates at this key evolutionary stage. Finally, two other examples of massive stars with longer periods include HD 15558 (O5e) and HD 193793 (WR), with periods of 1.2 and 7.9 years, respectively. At distances of 1.3 and 2.6 kpc, each system has a semimajor axis of 5–10 mas, easily within reach of SIM.

2.2.7. SPECIAL SAMPLE 2: White Dwarfs

At the end of a complicated stellar evolutionary process, white dwarfs are relics that slowly cool until they reach equilibrium with interstellar space. White dwarf cooling rates can therefore be used to place lower limits on the evolutionary ages of the disk, halo, and cluster populations. However, these cooling rates depend critically upon the mass of the white dwarf, the thickness of its envelope, and the compositions of its core and outermost layer. The mass of a white dwarf is usually derived from a spectroscopic determination of its surface gravity supplemented either with an estimate of its distance or through the application of a semi-empirical mass-radius relation (Wood 1995). Dynamical masses of modest accuracy have been determined for only 5 white dwarfs in binary systems, which is unfortunate because the masses determined from different methods often disagree by more than their errors (Koester & Reimers 1996). Such disagreement is primarily due to the difficulty in measuring surface gravities.

Calibrating the mass–radius relation for white dwarfs requires accurately known masses for a large sample of white dwarfs in binary systems (typically white and red dwarf pairs). The apparent distribution of periods for these systems is bimodal. The short-period systems are presumably a consequence of orbital shrinkage from common envelope evolution for stars with initial separations less than ~ 3 AU. The long-period systems formed via orbital expansion from post AGB mass loss. SIM's astrometric precision, coupled with its ability to disperse the fringes over its wide bandpass, will enable us to detect the reflex motions of both stars in short-period systems. A "visual" orbit can then be derived, and when combined with SIM's Global Astrometry on reference stars, the masses of each component can be found. A system such as the hot white dwarf Feige 24 (Benedict *et al* 2000a) illustrates the need for SIM. Feige 24 has a distance of 69 pc, an orbital period of 4.23 days, an estimated separation of $\sim$0.7 mas, and a magnitude difference of $\Delta V \sim 2$. The components' orbits are much larger than SIM's expected measurement limits. Our recent experience (Benedict *et al* 2000b) with the HST-FGS suggests that 10 pairs of orthogonal SIM measurements over a few days will provide masses for the Feige 24 system with $< 1\%$ errors. This would represent a huge improvement over the present model-based mass estimates of 0.21–0.47 $M_\odot$.

2.2.8. SPECIAL SAMPLE 3: Red Dwarfs

Red dwarfs dominate the solar neighborhood, accounting for at least 70% of all stars, and represent nearly half of the Galaxy's total stellar mass (Henry *et al* 1997). These stars have spectral type M, $M_V = 9$–20, and masses 0.08–0.60 $M_\odot$ (Henry & McCarthy 1993; Henry *et al* 1994). The MLR remains ill-defined for M dwarfs, so their contribution to the mass of the galaxy is a guess at best, and the conversion of a luminosity function to a mass function is problematic. At masses less than $\sim$0.2 $M_\odot$ an accurate MLR can provide a strict test of stellar evolutionary models that suggest the luminosity of such a low-mass star is highly dependent upon age and metallicity. Finally, the MLR below 0.1 $M_\odot$ is critical for brown-dwarf studies because accurately known masses can convincingly turn a candidate brown dwarf into a *bona fide* brown dwarf.

Over the last 10 years, several members of the MASSIF Team (Henry, Benedict, Nelan, and Torres) have determined the masses of red dwarfs using a combination of infrared speckle interferometry and HST-FGS. Our team has increased the number of stars on the lower main sequence with known masses from 4 to 12 (Henry *et al* 1999; Benedict *et al* 2000a). However, the masses of these stars are limited to errors of $\sim$5% because of "poor" parallaxes (errors ≥ 1 mas) and poor mass fractions (errors $\sim$1%). SIM is particularly critical for M dwarf systems because they are typically faint and do not allow high-precision radial velocity measurements due to their slow orbital motion and poorly separated spectral lines. As an example, we examine the nearby binary Gl 748, which currently has mass errors of 6% (Franz *et al* 1998). SIM can improve the masses by reducing the error in the semimajor axis of the absolute orbit (147.0 ± 0.7 mas) by a factor of 18 (to 0.04 mas, or 10 times the nominal astrometric accuracy of SIM for Global Astrometry) and the error in the parallax (99.2 ± 1.8 mas) by a factor of 45. The result would be mass errors of only 0.1%. The Gl 748 system has V = 11.12, so could be observed by FAME, but lower mass red dwarfs could not be, nor could the same system at the distance of the Pleiades.

2.2.9. SPECIAL SAMPLE 4: Brown Dwarfs

Two categories of brown dwarfs will be targeted in this Key Project: nearby L dwarfs, which represent the boundary between stars and brown dwarfs; and unseen brown dwarfs likely to be orbiting solar-type stars.

Mass is the best discriminator between stars and brown dwarfs. An object's mass determines whether or not temperatures in the object's core are sufficiently high to sustain hydrogen fusion — the defining attribute of a star. L dwarfs are objects with smaller masses and cooler temperatures (∼1500–2000K) than those of M dwarfs, but no masses of L dwarfs have yet been measured so the models of L dwarfs are completely untested by data. More than 100 L dwarfs have been discovered so far, and 3 of 10 targeted L dwarfs are resolved binaries (Koerner *et al* 1999) with periods of decades. L dwarf systems with smaller separations will almost certainly be found in the next few years. If L dwarfs are as prevalent as M dwarfs (and they appear to be), there will be ∼250 within 10 pc of the Sun and several will be bright enough to be targeted by SIM for mass determinations. Already, there are four L dwarfs with $V = 19$–23 and distances of 8–15 pc known (Reid *et al* 2000), and the search has barely begun.

The MASSIF Team will also target brown dwarfs found from radial-velocity surveys that are unseen companions of solar-type stars. These companions have minimum masses of $M \sin i = 12$–60 M_{Jup}. We will derive the companions' masses using SIM measurements of the system's photocentric orbit, the radial velocity orbit, and an assumed mass of the primary star (from the accurate MLRs constructed from the MASSIF cluster studies). The few dozen known systems of this type are ideal targets for SIM science, and will be superb targets for testing the imaging capabilities of TPF as it marches toward its ultimate goal of imaging Earthlike planets around nearby stars.

2.2.10. SPECIAL SAMPLE 5: The Exotics

Additional exotic targets that can and should be observed with SIM include embedded stars, T Tauri stars, cataclysmic variables, subdwarfs and halo stars. We take time here to outline a few of the more compelling cases of exotic objects — the supergiants, black holes, and globular cluster stars.

Supergiants At a distance of 2.3 kpc, η Carinae is one of the most luminous and presumably most massive objects in the Galaxy. Damineli *et al* (2000) present radial-velocity data suggesting that η Car is a massive binary with a period of 5.53 years and a highly eccentric orbit. (These measurements are challenged by Davidson *et al* 2000, however.) The result of its explosion in 1843 can be seen today as the expanding "Homunculus Nebula," a double-lobed structure (observed in exquisite detail by HST) bounded by a 15 $M_\odot$ equatorial torus (Morris *et al* 1999). The formation of this dense torus is possibly due to intense binary interaction. The binary orbit implies a maximum angular separation of 6 mas, which allows excellent mapping of the photocentric orbit with SIM (the primary star is much brighter than the predicted companion so the pair will not be resolved). Thus, SIM observations can potentially solve the mystery of the binary nature of η Car.

Black Holes The end-products of massive star evolution are neutron stars and black holes, and here, too, SIM observations will play a vital role in mass measurement. SIM measurements of the famous black-hole binary, Cyg X-1, will reveal a 36 μas variation over the 5.6 day orbital period. Combined with spectroscopic results (Gies & Bolton 1986), the MASSIF Team will learn the system's masses, distance, and the runaway velocity imparted by the supernova event (Nelemans *et al* 1999).

Globular Cluster Stars As superb examples of low metallicity objects, a few binaries in the globular clusters ω Cen and/or 47 Tuc will be targeted for mass determinations. Together with ground-based SB2 orbits, the SIM measurements would allow us to get fairly close to our strict criterion of 1% errors in the masses. As an example, at a distance of 4 kpc for ω Cen, a 1.5/1.0 $M_\odot$ pair in a 3 year orbit would have magnitudes of $V = 16.0$ and 18.0, and a semimajor axis of the absolute orbit of only 0.7 mas. Although the system would not be resolved, the photocentric semimajor axis (186 μas) and the parallax (250 μas) would both be within the reach of SIM, and when combined with the velocities high quality masses could be derived.

2.3. Science Measurements

2.3.1. Methodology for Mass Determinations

Historically, the determination of highly accurate masses for binary stars has required a combination of spectroscopic and astrometric measurements. The advent of global astrometry with interferometers, such as HST's Fine Guidance Sensors, has made the determination of such masses possible without radial velocities (Franz *et al* 1998; Benedict *et al* 2000a). Nevertheless, the best masses are found when complementary observing techniques are combined. For example, combined spectroscopic-astrometric solutions have been used in double-lined eclipsing binaries to reach mass errors of 2% (Andersen 1991). Unfortunately, small stars rarely eclipse and large stars are often interacting, so exemplary eclipsing binaries are not found for large portions of the main sequence (see Figure 1).

Table 2 lists the four types of binary orbits relevant to determining masses, as well as the orbital parameters that can be determined using the telescopes available to the MASSIF Team. To derive the dynamical masses of binary components using Kepler's Third Law, four parameters must be known: the period, the semimajor axis (in arcsec), the mass ratio (M_2/M_1), and the parallax. The first three types of orbits yield some, but not all, of the required parameters. Only the absolute astrometric orbit yields all four parameters. Nevertheless, combinations of various orbits can be used to derive masses. Here we outline the most likely scenarios for determining masses in the MASSIF Key Project.

Table 2. *Orbit Types in MASSIF Effort*

Orbit Type	specifics	Telescope	Parallax	Period	Semimajor Axis	Fractional Mass	Masses
Spectroscopic	SB2	HET, CfA	no	yes	asini only	yes	no
Astrometric	relative	CHARA	no	yes	yes	no	no
Astrometric	photocentric	SIM	yes	yes	photocenter only	no	no
Astrometric	absolute	SIM	yes	yes	yes	yes	yes

Cluster Targets — SB2 + SIM. All of our cluster targets will be chosen so that they exhibit double lines in their spectra (SB2s), from which the velocities of both components can be measured. SB2 solutions provide the period and fractional mass, but only lower limits to the semimajor axis ($a\ sin\ i$) and the masses of the individual stars ($M\ sin^3\ i$). SIM will provide all of the orbital elements needed to compute the masses, including the inclination, i. Together, the SB2 + SIM data will yield the most accurate masses ever achieved. SIM will also provide a trigonometric parallax that can be checked against the orbital parallax derived from the SB2 orbit and a relative astrometric orbit from a telescope like the CHARA Array.

The Special Samples in §2.2 include objects for which SB2 orbits will be difficult or impossible to determine to high accuracy. They can be grouped into the following two subtypes:

Special Targets — Relative Orbit + SIM. This case includes systems for which the relative orbit can be determined via a narrow field technique (such as with the CHARA Array), but for which no parallaxes or fractional masses can be determined spectroscopically. Pairs of OB stars, white dwarfs, the coolest red dwarfs, and brown dwarfs fall into this category. SIM will provide the parallaxes and fractional masses by measuring the targets' positions in Global Astrometry mode.

Special Targets — SB1 + SIM. This case includes systems for which only single-lined spectroscopic orbits are known because the companions remain unseen. Such systems include solar-type star/brown dwarf pairs and massive star/black hole pairs. The periods and parallaxes may be known *a priori*. SIM will yield the photocentric orbit, including the inclination, of the system relative to reference stars. The MLRs from the cluster work will be used to estimate the primary star's mass, which is the last element needed to determine the unseen companion's mass.

Many of the Cluster and Special Targets will be resolved by SIM (see Table 3), and the motions of each component will be measured against a grid of reference stars. In these cases, the SIM measurements alone will be sufficient to determine the masses and luminosity ratios. Spectroscopy will then provide a useful redundancy, particularly for systems close to SIM's resolution limit. On the other hand, systems with angular separations less than ∼2 mas will not be spatially resolved by SIM. In these cases, the inclination angle (and hence the masses) will be determined from the elements of the photocentric orbit.

2.3.2. Methodology for Luminosity Determinations

The luminosity (or absolute magnitude) of a binary component is the result of three measurements: the magnitude of the system, the brightness ratio of the two components (if not resolved), and the parallax. SIM will provide the parallax, and in most cases, spectroscopy will provide a first measure of the brightness ratio. The MASSIF Team will check and supplement these measurements with direct observations of the components using SIM, HST-FGS, the CHARA Array, and the Mount Wilson Adaptive Optics program. SIM permits measurement of the brightness ratio in as many as 80 bandpasses. Our team has fully characterized HST-FGS in the V band for binaries with magnitude differences up to 3 and separations as small as 20 mas. The CHARA Array will measure brightness ratios in the standard $VRIK$ bands for systems with separations as small as 1 mas, which is close to SIM's resolution limit. (CHARA magnitude difference limits are not yet determined.) The Mount Wilson 100in Adaptive Optics program can provide $UBVRI$ photometry for systems brighter than ~10 mag with magnitude differences of up to 10 and separations as small as 100 mas.

2.3.3. The Power of SIM

With its 10m baseline, SIM's fringes will be sensitive to structure in non-point source objects. By observing the fringe visibility as the delay line modulates across the object's white light fringe maximum, SIM will resolve binary systems down to projected separations of 2 mas (for modest magnitude differences). SIM is therefore a superb instrument for studying close binary systems that could not be resolved previously. Given adequate delay line modulation, the fringe morphology obtained from the observation of a binary star can be used to determine the separation and relative brightness of the system's components. Point source calibration fringes can be obtained by observing a grid star in the same field of regard, a capability we plan to exploit.

Table 3 lists the magnitudes and semimajor axes of hypothetical binaries in the five target clusters. The binaries have 3 year circular orbits and $\Delta V = 2.0$. We consider up to three binaries – a large OB pair, a medium FG pair, and a small M pair – spanning each cluster's main sequence. We have assumed worst-case absolute magnitudes, *i.e.*, those of stars with ages of the old disk (see Figure 1). All stars in the younger clusters will be brighter than the listed magnitudes. We list the semimajor axes of both the relative orbit (relevant if resolved by SIM) and photocentric orbit (relevant if not resolved by SIM). Systems with shorter periods will allow "repeat" SIM observations of parts of the orbits, and those with longer periods will have correspondingly larger separations.

For example, an OB pair in the Trapezium (d = 450 pc) with masses 25 and 10 $M_\odot$ and a 3 year period has apparent magnitudes of 4.3 and 6.3. The semimajor axes of their relative and photocentric orbits are 15.1 mas and 2.3 mas, respectively. SIM will resolve this system and render masses without need for spectroscopy, although radial velocities would assist in reaching 1% error. At the other brightness extreme is the M dwarf pair in M67. Its combined magnitude is at SIM's brightness limit (V = 20), and the system will be barely resolved. Nonetheless, accurate mass determinations are possible if the spectroscopic orbit is sufficiently accurate because SIM can provide the inclination of the photocentric orbit, which is 400 μas in size.

Table 3. *Hypothetical Cluster Binaries with 3 Year Periods*

		OB Stars		AFGK Stars		ML Stars	
		Primary	Secondary	Primary	Secondary	Primary	Secondary
mass		25 $M_\odot$	10 $M_\odot$	1.5 $M_\odot$	1.0 $M_\odot$	0.4 $M_\odot$	0.2 $M_\odot$
M_V		-4	-2	3	5	11	13
Cluster	Distance	V magnitudes Pri + Sec	Semimajor Axes Rel/Phot (mas)	V magnitudes Pri + Sec	Semimajor Axes Rel/Phot (mas)	V magnitudes Pri + Sec	Semimajor Axes Rel/Phot (mas)
Trapezium	450 pc	4.3 + 6.3	15.1 / 2.3	11.3 + 13.3	6.3 / 1.7	19.3 + 21.3	3.9 / 0.8
TW Hydrae	50 pc	none	none	6.5 + 8.5	56.5 / 14.9	14.5 + 16.5	35.1 / 6.9
Pleiades	110 pc	none*	none*	8.2 + 10.2	25.7 / 6.8	16.2 + 18.2	15.9 / 3.1
Hyades	45 pc	none	none	6.3 + 8.3	62.7 / 16.5	14.3 + 16.3	40.0 / 7.7
M67	800 pc	none	none	12.5 + 14.5	3.5 / 0.9	20.5 + 22.5	2.2 / 0.4

* The seven sisters of the Pleiades include B stars, but no O stars.

Table 4 lists several projects and their capabilities that may complement the MASSIF Key Project (the resolution limits listed represent sources of equal brightness that are generally brighter than the faint limits listed). The HST-FGS is currently being used by MASSIF Team members (Benedict, Henry, McArthur, and Nelan) to determine masses for red and white dwarfs. SIM will reach much fainter targets and determine orbits and parallaxes up to 100 times more accurately than FGS. The CHARA Array is a six-element optical/infrared interferometer with a maximum baseline of 354m. It will map accurate relative orbits of relatively faint objects, particularly at infrared wavelengths. The Array has no global astrometry mode, however, so parallaxes and fractional masses will not be obtained. Thus, binary masses will only be determined when the Array data is combined with radial velocity or global astrometry (*e.g.* SIM) data. The Keck and VLT interferometers have similar attributes. Both are large telescopes with baselines of ~100m, and both employ outrigger telescopes. Both will assist with determining stellar and substellar masses, but generally not to 1% accuracy. Because it is located in the southern hemisphere, VLTI cannot effectively observe the important Pleiades and Hyades clusters, and the Keck interferometer does not currently have a plan for accurate parallax determinations.

2.3.4. FAME and SIM

FAME will provide parallaxes for 40 million stars with magnitudes 5–15 to an advertised accuracy of 50–500 μas. Although FAME will be an impressive mission, these specifications are inadequate for determining the MLRs of even the nearest clusters.

Tables 3 and 4 indicate that *cluster red dwarfs are near or beyond FAME's limiting magnitude of V~15.* Because the metallicities and ages of red dwarfs are difficult to determine, nearby field stars will be inadequate to calibrate the important low-mass end of the MLR. Likewise, white dwarfs and candidate brown dwarfs are too faint for FAME. With a limiting magnitude of $V = 20$, SIM does not suffer these handicaps.

Table 4. *Projects Complementing MASSIF Effort*

	Date	Target Brightness Limit	Resolution Limit	Parallax Accuracy	notes
HST-FGS	now	V∼15	10 mas	500 μas	1 X 2.4m aperture
CHARA	2000	V∼10 K∼11	0.3 mas 1.3 mas	none none	6 X 1m apertures
KECK-Int	2001	K∼14	5.3 mas	none	2 X 10m + N X 2m apertures
VLTI	2002	K∼12	3.5 mas	10 μas	4 X 8m + N X 2m apertures
FAME	2004	V∼9 V∼15	400 mas 400 mas	50 μas 500 μas	1 X 0.6m aperture
SIM-NA	2006	V∼12	2 mas	1 μas	7 X 0.3m apertures
SIM-GL	2006	V∼20	2 mas	4 μas	

FAME's end-of-mission astrometric accuracy is 50–100 times poorer than SIM's. *Thus, FAME will measure photocentric orbits too crudely for use in determining highly accurate masses.* For example, the masses yielded by FAME for the OB pair in the Trapezium will have errors of 9.4% because the errors in the photocentric semimajor axis and parallax are 50 μas. Of all the binary's in Table 3, FAME's best result produces 1.1% mass errors for the the 1.5 and 1.0 $M_\odot$ pair in the Hyades. These examples assume no error in the periods and fractional masses. Thus, even at its best, FAME barely produces the 1% mass errors needed to challenge stellar models. Conversely, SIM's Global Astrometry will yield mass errors of 1% for the OB pair if the parallax and absolute semimajor axis are accurate to 4 μas and 40 μas, respectively. For the 1.5 and 1.0 $M_\odot$ pair in the Hyades, SIM will yield mass errors of only 0.2%. Clearly, the MLRs obtained from FAME observations of clusters beyond 50 pc will be poor substitutes for those obtained from SIM.

With a resolution limit of 0.4$''$ FAME will not resolve any cluster systems. Consequently, fractional masses cannot be directly determined. Although spectroscopy resolves this problem for many systems, it is difficult or impossible to obtain radial velocities for OB stars, white dwarfs, the coolest red dwarfs, and brown dwarfs of sufficient accuracy to reach 1% errors in the masses.

In summary, MLRs determined with FAME suffer the following limitations: (1) the cluster MLRs will lack low-mass stars, (2) mass errors will be much larger than 1%, and (3) most special sample targets will lack fractional mass determinations. Only SIM, with its faint limiting magnitude, exquisite astrometric accuracy, and high resolution capability, can provide the data required to derive accurate masses.

2.3.5. Observing with SIM

We will observe our targets in Global Astrometry mode. Our requirements for each Cluster Sample are (1) to observe 10 binary systems from which the masses of 20 components are derived, (2) to span at least an order of magnitude in mass, and (3) to determine masses to better than 1% so that stellar astrophysics models can be strictly challenged. Our requirements for each Special Sample are (1) to determine masses to better than 1% for 10 objects (the exact number of systems depends upon diversity of types), and (2) to span a factor of ten in metallicity for relevant samples. We will observe 50 systems from the five clusters and another 50 systems from the five special samples. These 100 binaries will be sprinkled among SIM's Global Astrometry targets, including the grid stars.

Our experience with HST-FGS, visual, and speckle astrometry indicates that ∼20 observations along a binary orbit are sufficient to obtain accurate orbital elements. According to the SIM AO Support guidelines for Wide-Angle Astrometry (AOS-WAA), the minimum number of one-dimensional observations required to derive parallax and proper motion for a target is 20. Our nominal observing plan is to quadruple this number to 80 observations/target to permit (1) accurate measurements along *both axes*, (2) deconvolution of proper motion, parallax, *and orbital motion*, and (3) determination of exact locations of resolved components.

According to AOS-WAA Table 2, Mission Time Per Target, targets with $V = 12$, 14, 16, 18, and 20 require 0.6, 0.7, 2.2, 10.7, and 59.6 hours of aggregate observing time, respectively, for an end-of-mission accuracy of 10 μas (an accuracy sufficient for most of our targets). We require four times the number of hours, or 2.4–238.4 hours/target for our nominal observing strategy. Clearly, only a few $V = 20$ targets can be observed. Table 3 reveals that most of our cluster targets have $V \leq 16$, corresponding to aggregate observing times of $\leq$ 8.8 hours/target, or 440 hours for 50 Cluster Sample targets. In the Special Samples, the bright OB stars (V<10, 10 targets, 24 hours) and solar-type stars with probable brown dwarf companions (V<10, 10 targets, 24 hours) will require little observing time. The faint red dwarfs (V∼16–18, 10 targets, 260 hours) and white dwarfs (V∼16–18, 10 targets, 260 hours) require substantially more time. We also allocate 1000 hours to observe some important brown dwarf targets that are near the detection limit of SIM. We therefore estimate 440 hours for the Cluster Samples, 568 hours for the Special Samples, and 1000 hours for the most important faint targets, for a total of ∼2000 hours. The timing of observations will be determined by the orbital periods and phases of the binaries, but we anticipate a fairly even spread throughout the 5 year lifetime of SIM. For ∼100 systems, this corresponds to 400 hours/year or about 8% of available observing time over the lifetime of the mission. Should the very faint objects prove too expensive in observing time, they will be sacrificed and the Cluster and Special Samples will be augmented. Finally, we intend to use the "chaff" from the grid stars — those that turn out to be binaries — to determine additional stellar masses and thereby increase the scientific payoff of the MASSIF Key Project.

2.3.6. Supporting Observations

CHARA Array — access by Gies, Henry; operational Fall 2000. Built by Georgia State University, the CHARA Array is dedicated to interferometry and imaging. It consists of six 1m telescopes in a Y-configuration with a 354m maximum baseline, and yields 0.3 mas resolution at V and 1.3 mas resolution at K. It uses standard $VRIK$ filters, with limits of V = 10, K = 11 under average seeing conditions and adaptive optics. The CHARA Array will be used to map relative astrometric orbits and determine brightness differences. *CHARA's ability to observe in the IR mitigates the problem of potentially large magnitude differences* *present at visible wavelengths.*

Hobby Eberly Telescope (HET) — access by Benedict, McArthur; operational now. Built by the University of Texas, Pennsylvania State University, and three minor partners, HET is a 9.2m telescope dedicated to spectroscopy. HET's High Resolution Spectrograph (HRS, R = 60000) has throughput similar to Keck's HIRES, giving S/N= 100 for a $V = 14.5$–15.0 star in one hour. HRS was designed to make radial-velocity measurements to a precision of 3 m/s or better. We will use HET to determine spectroscopic orbits and determine brightness differences for a large sample of SIM targets. *The HET/HRS combination along with its queue scheduling mode of operation is an ideal instrument for determining the radial velocity variability of a large sample of SIM targets.*

CfA Telescopes — access by Torres; smaller telescopes operational now; MMT operational Fall 2000. The CfA telescopes will be used to select candidates in all clusters except the TW Hydrae Association. Long-term observing programs have already been carried out on the Hyades, Pleiades, and M67. Rich datasets are now available for target selection.

Adaptive Optics at Mount Wilson — access by all; operational now. Now run as a consortium, the Mount Wilson Institute utilizes the 100in Hooker Telescope. The adaptive optics program provides $UBVRI$ photometry for systems brighter than mag$\sim$10 with magnitude differences of up to 10 and separations as small as 100 mas. Observations at Mount Wilson will be used to resolve wide binaries at various wavelengths.

Sloan Digital Sky Survey — access by Golimowski; operational now. Operated by Princeton University, Johns Hopkins University and seven other partners, SDSS is an imaging and spectroscopic survey of one quarter of the northern sky to magnitude limits of 20 or more in five bands (*ugriz*). It is well suited for identifying stars spanning SIM's range of sensitivity. Results from SDSS will be used to select new nearby white, red, and brown dwarf candidates for mass determinations.

CTIOPI — being carried out by Henry, Ianna; operational now. The Cerro Tololo Interamerican Observatory Parallax Investigation (CTIOPI) targets faint, southern stars — primarily white, red and brown dwarfs — that are missing from the sample of nearby stars. The CTIO 0.9m and 1.5m telescopes are used to obtain parallaxes, proper motions, and *VRI* photometry. When combined with Ianna's observations over the past decade at Siding Spring Observatory, perturbations as long as 10 years will be revealed. Targets exhibiting perturbations from unseen companions will be ideal targets for the MASSIF Key Project.

USNO Astrograph — access by Mason; operational now. This all-sky survey by the United States Naval Observatory measures positions and proper motions to accuracies of 20 and 70 mas for magnitudes 14 and 16.5 (at 6100±630 Å), respectively. Results from the USNO Astrograph will be used to identify new members of all five clusters.

Henry brings to the SIM Science Team not only expertise in tackling important astrophysical questions, but a high energy level and the prospect of continuity to the project. SIM is a long-term mission, and the advantage of having some younger members on the Science Team cannot be overlooked. Henry will contribute to the SIM Science Team in two roles, both for the science community and the public.

Henry is uniquely qualified to play the role of "star guru" for SIM Science Team. He has been working on the sample of stars nearest to the Sun since 1986, and leads an effort known as RECONS (Research Consortium on Nearby Stars) to characterize all stars within 10 pc. One of RECONS' most important results to date is the discovery of the twentieth nearest star, GJ 1061 (Henry *et al* 1997), only 3.7 pc away. These experiences resulted in Henry being appointed as a Project Scientist for NASA's NStars Project in 1999, for which he is providing the fundamental data for all stars within 25 parsecs. In this capacity he has already provided observing lists for HST, SIRTF, and (for proposals for) SIM. Henry has experience in *VRIJHK* photometry, optical spectroscopy, optical and infrared speckle interferometry, and CCD astrometry, all of which can and should be used to characterize the SIM targets. Henry has completed surveys for companions to nearby red dwarf and solar-type stars, has made measurements of stellar activity for ~1000 solar-type stars, has established a fundamental spectral sequence for red dwarfs, and has provided the best available calibration of the stellar mass-luminosity relation. This last accomplishment includes leading the longest-term program (6 years) using the only interferometer currently in space — the Fine Guidance Sensors on HST. Henry is also leading a new initiative to discover ~200 new nearby stars in the southern hemisphere via parallax work in Chile at CTIO, so is positioned to add many new targets to the SIM pool in the southern sky. After joining the Georgia State University faculty in August 2000, Henry has access to the CHARA Array on Mount Wilson to detect stellar companions to SIM candidate stars using both narrow-angle astrometric and imaging capabilities. Given his long-term commitment to discovering and characterizing the nearby stars, assuming the role of star guru for the SIM Project is a natural assignment.

Henry has a deep commitment to community and public service, and is a valuable liaison with the public. He has developed compelling articles and graphics for both the film (Cinenova) and print (National Geographic; Air and Space Magazine; Sky & Telescope; various textbooks) media. A unique contribution that Henry will make to the SIM Science Team is the possibility of creating dramatic visualizations of SIM's scientific discoveries and technological accomplishments. Henry has already made a connection with the Georgia State University Film Department, which is one of the top-notch film departments in the nation. In collaboration with the Art, Film, and Computer Sciences Departments, we plan to create scientific films in formats ranging from VHS to IMAX that convey the wonders of our solar system, stars and stellar evolution, and the search for planets elsewhere. The first project, already outlined, is a fly-through of the solar system and the nearest stars, with close inspection of the Alpha Centauri system. Other scientific programs included in the SIM effort could be incorporated into the film work and provide an excellent way to inform the public about the SIM Project.