The Mass-Luminosity Relation and Space-based Interferometery: from Hubble Space Telescope to the Space Interferometry Mission

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ABSTRACT

With a white-light interferometer (Fine Guidance Sensor 3) on the *Hubble Space Telescope* (*HST*) we have secured fringe scanning and fringe tracking observations to measure distances, orbits, and, hence, masses, for several nearby low-mass stars. We have made progress towards a more precise Mass-Luminosity Relation (MLR) for the lower Main Sequence. However, the MLR is a map whose low mass region is complicated by relative and absolute age and whose high-mass end is very poorly determined. To begin to disentangle these effects, and to obtain high-precision mass determinations throughout the Main Sequence, we will participate in the *Space Interferometry Mission* (*SIM*) to observe binary stars of all masses in five star clusters with a large range of well-known ages and chemical compositions. We will also observe a sample of stars throughout the Main Sequence. The unparalleled angular resolution and limiting magnitude of *SIM* will allow us to obtain masses precise to 1%.

Keywords: Astrometry, interferometry, *Hubble Space Telescope*, *Space Interferometry Mission*, binary stars, stellar parallaxes, stellar masses

1. INTRODUCTION

With the exception of the H-R diagram, the MLR is perhaps the single most important "map" of stellar astronomy. The mass of a star is the key parameter governing its entire evolution. For single objects, the MLR allows astronomers to convert a relatively easily observed quantity, luminosity, to a more revealing characteristic, mass, thus yielding a better understanding of the object's nature. In the broader context of galactic astronomy, an accurate MLR permits a luminosity function to be converted to a mass function, and drives estimates of the stellar contribution to the mass of the Galaxy. Directly relevant to *SIM* science, determining precise masses for extrasolar planets requires knowing precise masses for their parent stars.

Space-based interferometry already exists. With a Fine Guidance Sensor on the *HST* we have secured fringe scanning and fringe tracking observations to measure distances, orbits, and, hence, masses, for a handful of nearby low-mass stars. We have made substantial progress towards a Mass-Luminosity Relation (MLR) for the lower Main Sequence, which we review below. However, these field stars have uncertain ages and metallicities, and the MLR is a map whose low mass region is complicated by relative age (M stars descend slowly to the Main Sequence) and absolute age (M star luminosity is affected by composition, which is a function of birth date in the Galaxy).

Our *SIM* Mass-Luminosity Relation Key Project will observe binary stars of all masses in five star clusters with a large range of well-known age and chemical composition. The unparalleled angular resolution and limiting magnitude of *SIM* will allow us to obtain masses precise to 1%, even in our most distant cluster (M67, D=800pc).

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In addition to a Mass-Luminosity-Age-Metallicity Relation for the entire Main Sequence, we will provide direct mass determinations for a representative sample of stellar exotica, including white dwarfs, neutron stars, and black holes.

Why is a mass precise to 1% such a desirable goal? When testing the accuracy of results, stellar modelers compare with real stars. Our knowledge of stars consists of surface temperature, T_e; apparent magnitude; metallicity; distance, hence luminosity, and through T_e, radius; and stellar mass, $\mathcal{M}$. At a 5% level of mass precision the variation in absolute magnitude due only to mass uncertainty ranges from 12 to 22% over the mass range, $0.1 < \mathcal{M} < 10\mathcal{M}_\odot$. This luminosity uncertainty means, for example, that radii would be very poorly determined, rendering them far less useful as checks of stellar models. At the 1% level of mass precision the variation in absolute magnitude is only 2 to 4%. Such precision will improve comparisons with these very real stars. This precision will allow choices to be made between various modeling approaches and the inclusion and modeling of stellar phenomena such as convection, mass loss, turbulent mixing, rotation, and magnetic activity (Andersen[1,2]).

2. THE MLR: WHAT HAS AND WILL BE DONE WITH *HST*

HST has on board three white light interferometers, called Fine Guidance Sensors (FGS). Two are used as to stabilize the telescope. The third FGS can be used to either inspect the fringe produced by the FGS (fringe scanning) or as a classical astrometer, measuring relative positions within the pickle-shaped total field of view (fringe tracking). The FGS is described in detail by Bradley *et al.*.[9] Franz *et al.*[12] describe fringe scanning observation and reduction techniques, and Benedict *et al.*[7,8] discuss fringe tracking observations and reduction techniques.

Briefly, two photomultiplier tubes measure the output from the two faces of a Koester's prism, the interfering device. The signals are combined, $S = (A-B)/(A+B)$, to form the fringe. Figure 1 contains a Y-axis fringe for FGS 3. Fringes are formed for two orthogonal axes, through two orthogonal Koester's prisms, allowing for a simultaneous measurement along both the X and Y axes. For fringe tracking FGS electronics extract the S_Y zero crossing location 40 times a second. A position measurement is the median of over several thousand such extractions. Because a fringe from a binary system is the linear superposition of the fringe due to each component, fringe scanning data can be decomposed, yielding component separation, position angle, and the magnitude difference (Δm). One such decomposition is shown in Figure 1.

Recent results from fringe scanning relevant to the MLR include a binary star relative orbit (Franz *et al.*[12]) and measures of component separation and Δm for a number of low mass binary stars (Henry *et al.*[16]). Recent results from fringe tracking include the absolute orbits of the binary systems Gl 791.2 (Benedict *et al.*[5]) and Wolf 1062 (Benedict *et al.*[4]). The orbits derived for the second system are shown in Figure 2. The orbit of the primary comes from fringe tracking measurements of the primary. The orbit of the secondary comes from deconvolved fringe scans yielding separations, position angles, and Δm. In other words, fringe scanning data are used to obtain relative positions of the A and B components; fringe tracking data are used to obtain the photocenter position of component A relative to a reference frame. Various combinations of these techniques resulted in the determination of component masses and absolute magnitudes, now gathered to define the MLR seen in Figure 3.

We have not yet finished exploiting *HST* in aid of the MLR. We have secured fringe tracking and fringe scanning measurements with which to define absolute orbits and, hence, masses for two other low-mass systems, Gl 623 and Wolf 922. These are being analyzed with publication to come shortly. In addition to these, we are in the process of obtaining smaller sets of *HST* FGS data (mostly fringe scanning) on 9 other low mass systems. Combined with radial velocity measures (acquired with the McDonald Observatory 2.1m and Cass Echelle spectrograph), now spanning over seven years, and analyzed as in Benedict *et al.*,[4] we expect to obtain masses precise to better than 5% for 18 components, significantly filling in the Figure 3 lower Main Sequence MLR.

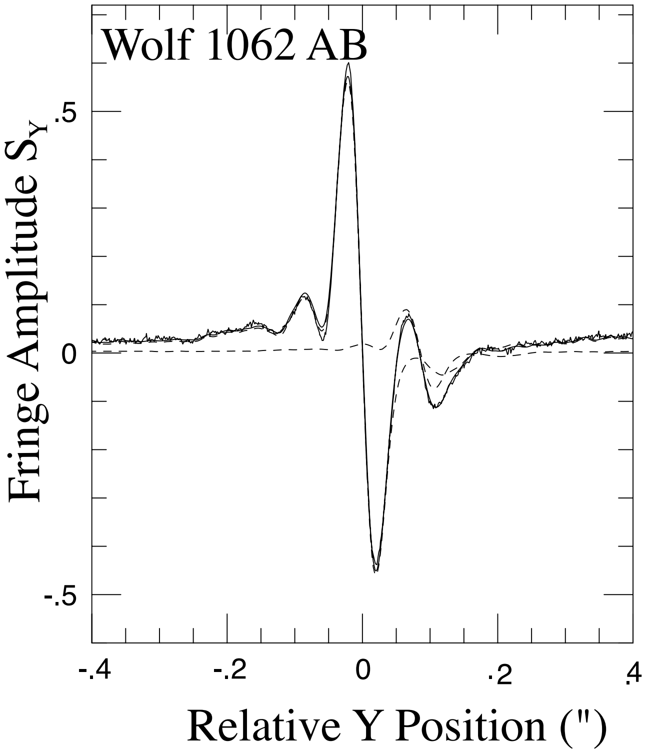

Figure 1. A Y-axis fringe from FGS 3. Techniques involving fringe scans use the entire fringe morphology to detect structure, the simplest being the presence of two stars, rather than just one star. In this case the two components (whose individual fringes are shown as dashed lines) were separated by 86.2 mas, with Δm = 1.8 (Franz *et al.*[12]). Some of the fringe structure is due to the misfigured *HST* primary mirror and small misalignments within the FGS. Fringe tracking extracts the position at which the fringe crosses zero.

3. THE MLR: WHAT WILL BE DONE WITH *SIM*

The principal goals of the *SIM* MASSIF (Masses and Stellar Systems with Interferometry) 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 $\mathcal{M}_{\odot}$. 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.

Despite its broad utility, the MLR remains poorly defined for many regions of the H-R Diagram. Figure 4[15] 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 $\mathcal{M}_{\odot}$; at $M_V = 5$, 0.8–1.4 $\mathcal{M}_{\odot}$; at $M_V = 10$, 0.28–0.6 $\mathcal{M}_{\odot}$; at $M_V = 15$, 0.12–0.22 $\mathcal{M}_{\odot}$. 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 ($\mathcal{M} >$

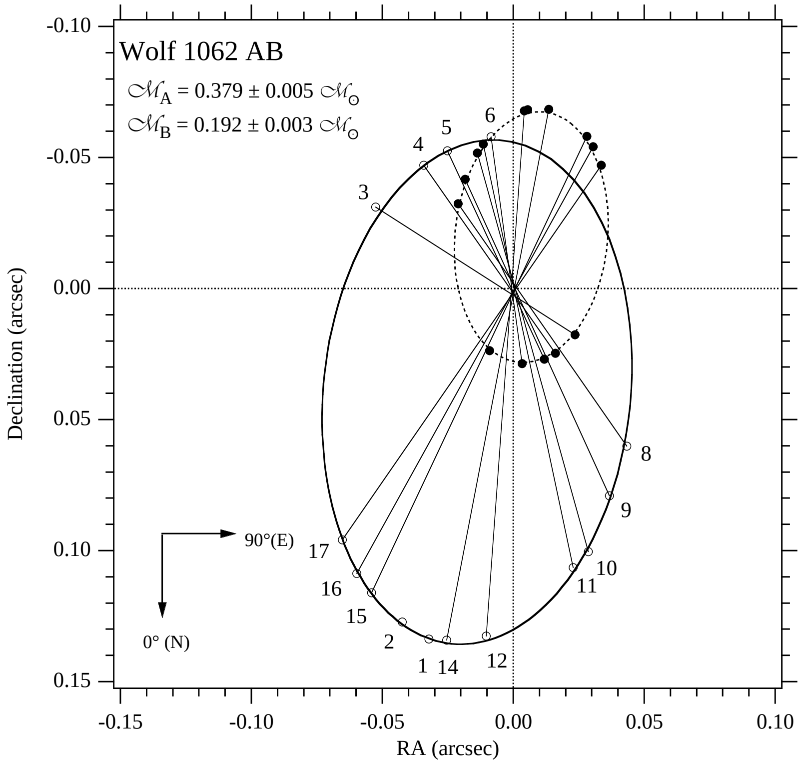

Figure 2. Wolf 1062 A (dots, fringe tracking measurements) and component B (open circle, fringe scanning measures). FGS observations and A and B component radial velocities were used to derive the orbital elements (Benedict *et al.*[4]). Our orbit solutions and associated absolute parallax provide an orbit semi-major axis, a in AU, from which we can determine the system mass through Kepler's Law. Given P and a, we solve the expression $a^3/P^2 = (\mathcal{M}_A + \mathcal{M}_B) = \mathcal{M}_{tot}$ and find $\mathcal{M}_{tot} = 0.571 \pm 0.008\mathcal{M}_{\odot}$. At each instant in the orbits of the two components around the common center of mass, $\mathcal{M}_A/\mathcal{M}_B = \alpha_B/\alpha_A$, a relationship that contains only one observable, α_A, the perturbation orbit size. We, instead, calculate the mass fraction $f = \mathcal{M}_B/(\mathcal{M}_A + \mathcal{M}_B) = \alpha_A/(\alpha_A + \alpha_B) = \alpha_A/a$, where α_B =a$-\alpha_A$. This parameter ratios the two quantities directly obtained from the observations; the perturbation orbit size (α_A from fringe tracking mode) and the relative orbit size (a from fringe scanning mode). From these we derive a mass fraction, f = 0.3358 ± 0.0021, hence, $\mathcal{M}_A = 0.379 \pm 0.005\mathcal{M}_{\odot}$ and $\mathcal{M}_B = 0.192 \pm 0.003\mathcal{M}_{\odot}$, masses precise to 1.5%.

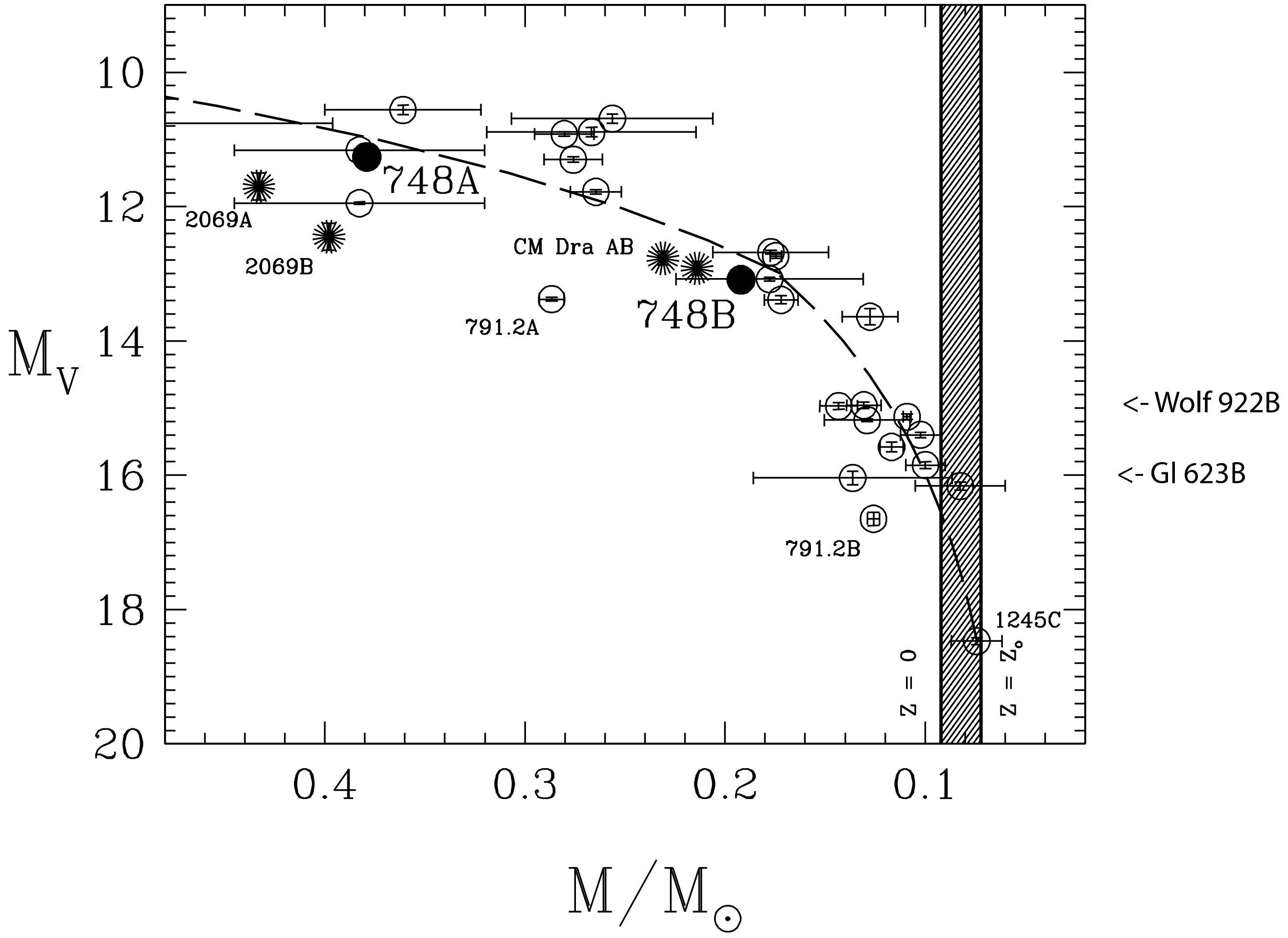

Figure 3. Stars on the lower Main Sequence mass-luminosity diagram. For Wolf 1062 (Gl 748 AB in the plot) the point size is representative of the mass errors. Other stars of interest are labeled, including the four components of the GJ 2069 (Delfosse *et al.*[11]) and CM Dra (Metcalfe *et al.*[19]) eclipsing binary systems (starred points) and the recent determinations for Gl 791.2 AB by this group (Benedict *et al.*[5]). Also labeled is GJ 1245C, still the lowest mass object for which an accurate dynamical mass has been determined. The dashed curve is the empirical mass-luminosity relation from Henry and McCarthy[17] down to 0.18 $\mathcal{M}_\odot$ and from Henry *et al.*[16] at lower masses. The shaded region with borders at 0.092 and 0.072 $\mathcal{M}_\odot$ marks the main-sequence minimum mass range for objects with zero to solar metallicity. The right axis shows the location of the lower mass components of two systems whose analysis is near completion.

20 $\mathcal{M}_{\odot}$) and lower ($\mathcal{M} < 0.20\mathcal{M}_{\odot}$) Main Sequence, and these masses typically have errors in excess of 10% (Harries *et al.*[13]; Henry *et al.*[16]). Another example of why the MLR must be improved is evident in Figure 1: at masses below 0.8 $\mathcal{M}_{\odot}$ only one of the three eclipsing binaries known falls on the empirical MLR of Henry & McCarthy.[17] Clearly, efforts to disentangle the relations between mass, luminosity, age and metallicity have barely begun.

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. MASSIF's efforts to map 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.*[24]). However, the Hyades MLR extends only from 2.4 to 0.8 $\mathcal{M}_{\odot}$ 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.

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

- 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.
- Challenge stellar astrophysics models by obtaining masses and luminosities accurate to 1%.
- Provide a "toolbox" full of MLRs at $UBVRIJHK$ wavelengths as a function of age and metallicity.
- 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?
- 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.
- 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.

Our goal is to determine masses for 10–20 objects in each of the 10 categories listed in Table 1. Two categories are described below. 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[14]). 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.*[20]), we should have no problem identifying suitable targets in the clusters.

Table 1. *MASSIF Targets*

Cluster or 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	< 70 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.

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.

We point out that our particular *SIM* Key Project would greatly benefit from having access to at least one entire *SIM* fringe, rather than only fringe tracking measurements at 80 wavelengths between 400 and 900 nm. To illustrate our approach with *SIM* we now discuss one cluster and one special sample in more detail.

CLUSTER SAMPLE: 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 ($\mathrm{m}-\mathrm{M} = 5.35$) 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 (e.g., Pinsonneault *et al.*[21]).

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 $\mathcal{M}_\odot$, corresponding to spectral types as late as M5. At least nine SB2s have already been identified in the Pleiades (e.g., Soderblom *et al.*[23]). Of these, HII 173, a K0V SB2 with a period of 480 days, has a semimajor axis of ∼13.0 mas. With a deconvolved fringe *SIM* will be able to measure both orbits of this binary pair, and hence the component masses, to better than 0.2%. A hypothetical M dwarf binary with $\mathcal{M}_A = 0.4\mathcal{M}_\odot$ and $\mathcal{M}_B = 0.2\mathcal{M}_\odot$ would have component apparent magnitudes of $\mathrm{V} = 16.2$ and $\mathrm{V} = 18.2$. With a three year period the primary would have a photocenter orbit semi-major axis $\alpha_A = 3.1$ mas with the system component separation, $a = \alpha_A + \alpha_B = 15.9$ mas, again, easily resolvable with a deconvolved *SIM* fringe.

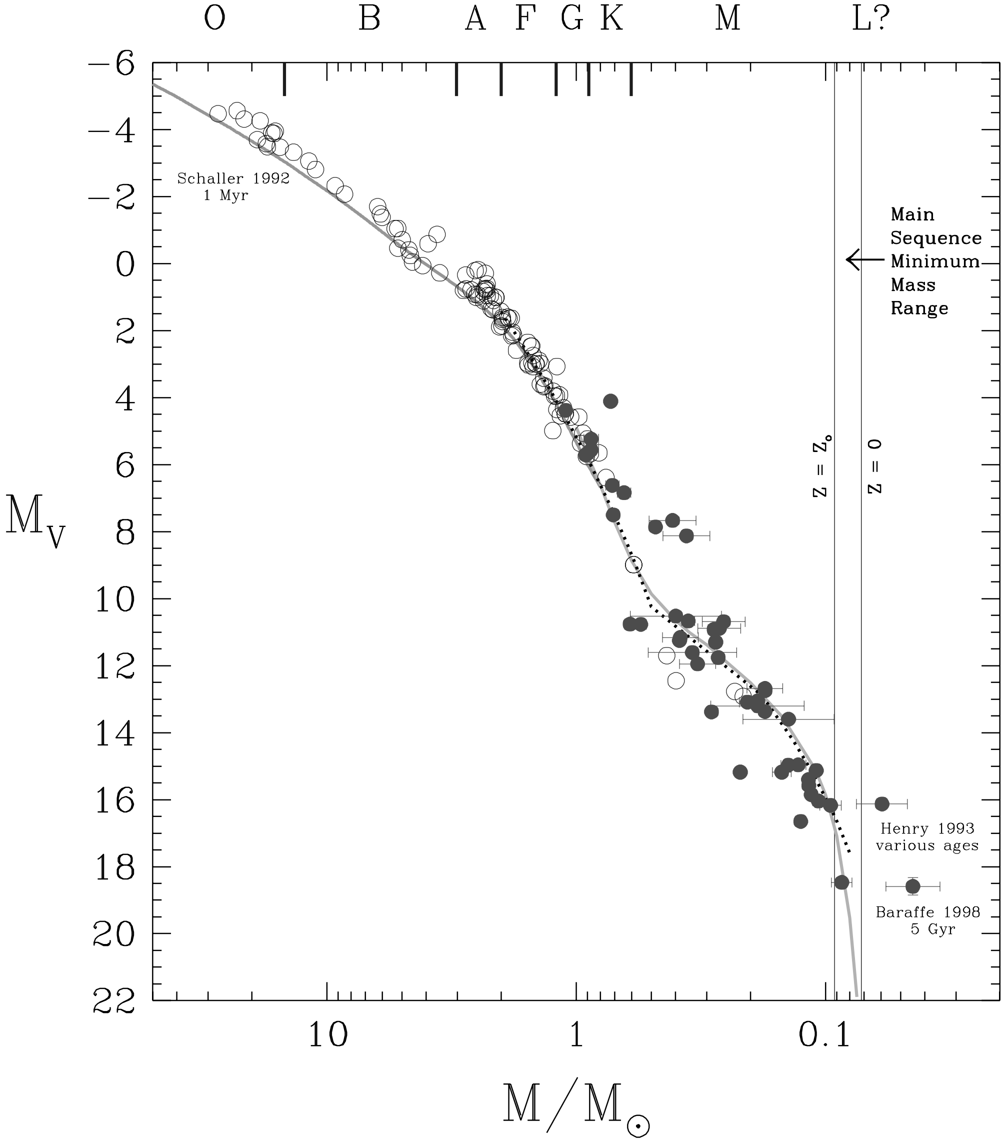

Figure 4. The Mass-Luminosity Relation at optical wavelengths for field stars is shown (Henry & Torres[15]). Masses from 30 $\mathcal{M}_\odot$ to 0.08 $\mathcal{M}_\odot$ are represented by open points for eclipsing binaries and solid points for astrometric binaries. The region from 0.092 and 0.072 $\mathcal{M}_\odot$ 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.*[22] and for low mass stars from Baraffe *et al.*,[3] and empirical fits (dotted line) from Henry & McCarthy[17] and Henry *et al.*.[16] Each fit has a terminus near 1 $\mathcal{M}_\odot$.

SPECIAL SAMPLE: 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. Dynamical masses of modest accuracy have been determined for only a few white dwarfs in binary systems, which is unfortunate because the masses determined from different methods often disagree by more than their errors (Koester & Reimers[18]). 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* reference star Global Astrometry, the masses of each component can be found. A system such as the hot white dwarf Feige 24 (Benedict *et al.*[6]) 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.*[4]) 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 estimate range 0.21–0.47 $\mathcal{M}_{\odot}$. In this case (the binary components have significantly different colors) the work could be carried out with fringe tracking measurements at 80 wavelengths between 400 and 1000nm.

4. THE ADDED VALUE OF RADIAL VELOCITIES

Radial velocities are a critical element in the success of our MLR investigation. First, they enable the discovery of suitable binary systems. Second they characterize the systems, substantially improving the accuracy of determined masses. To discover and characterize later type binaries with later type companions in our clusters will require high S/N doppler spectroscopy at $V > 13$, a task for a large telescope such as the 9.2m Hobby-Eberly Telescope. Regardless of the astrometer employed, be it *HST*, *CHARA*, or *SIM*, the **accuracies** of our masses are improved by incorporating radial velocity data obtained through doppler spectroscopy. By measuring the same physical process (the orbital motion) in three dimensions, two from astrometry, the third from radial velocity, and by insisting that we obtain the same results for orbital period, eccentricity, and orientation, the two approaches 'check' each other and improve the accuracy of the result. Such a partnership requires the highest precision radial velocities, again, for the faintest candidates in our study best delvered by a telescope like the Hobby-Eberly Telescope (Cochran *et al.*[10]).

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