III

Precision Stellar Astrophysics

> WATCH THE STARS,
> AND FROM THEM
> LEARN.
>
> *Albert Einstein*

What is the most massive star?

What is the stellar mass content of the Galaxy and how does it evolve?

How do stellar properties vary with metallicity and age?

What are the total luminosities and jet velocities of X-ray binary microquasars?

What are the masses of black holes and neutron stars and the neutron star equation of state?

Where are the sources in various radio-emitting stars?

What is the nature of the mass-loss process in asymptotic giant branch stars?

How will parallax distances improve applications of main-sequence fitting of star clusters?

What are the ages of metal-poor stars in the Milky Way halo and globular clusters?

8 Stellar Maps with SIM Lite

Todd J. Henry (GSU), **Douglas R. Gies** (GSU), **Wei-Chun Jao** (GSU), **Adric R. Riedel** (GSU), **John P. Subasavage** (GSU), **G. Fritz Benedict** (U Texas), **Hugh C. Harris** (USNO), **Philip A. Ianna** (U Virginia), **John R. Thorstensen** (Dartmouth College), **Charles Beichman** (NExScI), **Lisa Prato** (Lowell Observatory), and **Michal Simon** (SUNY Stony Brook)

ABSTRACT

Stellar astronomy is largely based on two maps, the Hertzsprung-Russell diagram and the mass-luminosity relation. Because of its reach into the Galaxy and its flexible observing modes, SIM Lite can make substantial contributions to both of these fundamental stellar maps for relatively rare objects, for which large populations are not found until the observing horizon reaches hundreds or thousands of pc. SIM Lite also effectively has no bright limit for stellar targets, so it can pinpoint the locations of every star seen by the naked eye in the night sky. Among these stars are the nearest massive O stars and bright supergiants that SIM Lite can place on the Hertzsprung-Russell diagram with unprecedented precision. Precise distances to the rare central stars of planetary nebulae can also be determined by SIM Lite, allowing them to be placed on the Hertzsprung-Russell diagram and permit the physics of their surrounding nebulae to be understood in more detail than ever before. For the mass-luminosity relation, SIM Lite will determine exquisitely accurate masses for stars in fundamental clusters, young stars, massive O stars, subdwarfs, and white dwarfs. With an extensive collection of high-accuracy masses from SIM Lite, astronomers will be able to "stress test" theoretical models of stars as never before.

8.1 SIM Lite and Gaia

Both the Gaia and SIM Lite efforts will revolutionize our understanding of stellar astrophysics via the Hertzsprung-Russell diagram (HRD) and the mass-luminosity relation (MLR), albeit in different ways. Gaia's high-precision astrometry of one billion sources will provide superb measurements of luminosities, temperatures, and masses of most of the stellar main sequence, giants, subdwarfs, and white dwarfs. More specifically, Gaia will determine distances to 1 percent for 10^7 stars having V = 6 to 13 within ~1 kpc (Lindegren et al. 2008).

SIM Lite provides complementary depth to Gaia's astrometry in specific regimes of both magnitude and distance. SIM Lite can effectively observe stars with V = –1.5 to 20, adding complementary phase space at bright magnitudes to Gaia's bright cutoff at V ~ 6 and making more accurate astrometric measurements at the faint end. Thus, only SIM Lite can pinpoint the locations of many of famous naked-eye stars in the night sky while opening up new territory for intrinsically faint stars at tens or hundreds of pc. For magnitudes 6 to 13, SIM Lite's wide-angle mode parallax precision of 4 µas is modestly better than Gaia's 8 µas, which will observe a far larger stellar sample. For magnitudes 14 to 20, SIM Lite's precision is 3 to 70 times better than Gaia's (Lindegren et al. 2008). By combining SIM Lite's somewhat better precision at moderate magnitudes with its increasingly better precision at faint magnitudes, accurate masses for suites of pre-main-sequence to solar-aged stars in specific clusters can be measured to reveal how the MLR changes over time. In addition, samples of intrinsically faint subdwarfs and white dwarfs can be targeted by SIM Lite for accurate mass measurements.

The combination of the ability to observe bright objects at all, and faint objects with superior precision, provides several niches important to stellar astronomy that only SIM Lite can explore. In what follows, we provide details of several astrophysical locations on the HRD and MLR stellar maps that are ideally suited for SIM Lite's attention. Table 8-1 lists representative parameters for the observational programs discussed below that could be carried out to define the HRD and MLR stellar maps. Ultimately, the goal is to pinpoint each type of star's location on the HRD so that the effects of age, metallicity, rotation, magnetic fields, spots, convective overshoot, and meridional circulation can be disentangled. Then, matching stellar luminosities to masses via the MLR would permit us to fundamentally understand stellar astrophysics. A 1 percent threshold in luminosity and mass measurements is adopted for the discussion that follows because evolution within the main sequence causes the observed ranges in luminosity and mass to be at least 15 percent for a given stellar color or temperature (see Andersen 1991; Henry et al.

Table 8-1. Example SIM Lite observing programs for stellar maps.

Object	Mag Range	No. Objects	No. Visits per Object	Integration Time, s	Parallax Error, µas	Distance Reached	Error	Time, hrs
HRD Map								
O Stars	2–12	259	100	10	4–5	2.5 kpc	<1.3%	287
Supergiants	<6	219	80	10	4	2.5 kpc	<1.0%	195
PNe	<17	170	20–50	15–800	4–14	8.5 kpc	<10%	170
MLR Map								
M34 Cluster*	11–16	12	100	30	4–10	400 pc	<0.2%	10*
Young Stars	9–18	20	100	30–120	4–20	1.0 kpc	<2%	46
O Stars	2–12	20	100	10	4–5	1.0 kpc	<0.4%	22
Subdwarfs	8–14	15	100	30	4–5	100 pc	<0.1%	25
White Dwarfs	15–18	20	100	30–120	5–20	200 pc	<0.4%	66

* Representative cluster for the MLR work. Many clusters could be studied with SIM Lite with somewhat more or less observing time devoted to each depending on the number of binaries targeted and their brightnesses.

2006, Figure 2; and Figures 8-1 and 8-2 in this chapter). Given an understanding of the effects of age — which result in changing stellar radii, luminosities, and temperatures for stars of a given mass — it may be possible to reduce the scatter to 5 percent (Andersen 1991), at which point metallicity and other effects come into play. Thus, if we can determine both luminosities and masses to 1 percent, we have some hope of unravelling the many causes of the variations seen in stars.

8.2 The Hertzsprung-Russell Diagram

The HRD is generally the first figure a stellar astronomer considers to understand any given star in context. All different classes of stars appear on the HR diagram, including supergiants, asymptotic giant branch (AGB) stars, giants, subgiants, dwarfs, subdwarfs, and white dwarfs, as well as other exotic stars. The HRD maps a star's temperature and luminosity, which together determine the star's radius. However, placing a star on the HRD requires knowledge of its luminosity, and, hence, an accurate distance measurement. Trigonometric parallax is the most reliable and straightforward method of measuring stellar distances, and is usually the most accurate method as well. Ground-based parallax efforts have continued for 170 years (van Altena et al. 1995) with continuing efforts collected in the RECONS Parallax Database (Research Consortium on Nearby Stars, www.recons.org). In the past 20 years, space-based efforts have made great headway, both in sheer numbers (Hipparcos, ESA 1997; van Leeuwen 2008) and precision (Hubble Space Telescope, Benedict et al. 2007).

In the coming era, astrometric efforts like the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), the Large Synoptic Survey Telescope (LSST), and Gaia will measure parallaxes of millions of stars to unprecedented precision. Even so, SIM Lite has much to offer to the HRD because it can reach further into the Galaxy than any other instrument and will, therefore, measure accurate distances to rare, astrophysically compelling objects.

8.2.1 Massive Stars

The massive O* stars are among the brightest objects observed in galaxies and they play a central role in sculpting the interstellar medium (ISM) through their radiative and mechanical energy input, while driving the chemical enrichment of galaxies. With lives of only a few million years, they quickly burn through their fuel and explode catastrophically in supernovae. However, the fundamental parameters of these extraordinarily rare stars are still poorly known because they are generally found at large distances. Some O stars are found in clusters, but roughly 20 percent are runaways or field O stars, while many others are found in loose associations with poorly defined boundaries and distances; e.g., the Cep OB6 association has a 3 degree extent and a consequent 5 percent dispersion (1σ) in distance (Benedict et al. 2002).

The placement of massive stars in the HRD relies heavily at present on model atmosphere results that need thorough verification. Hot stars all have essentially the same colors in the optical/IR spectral range (after correcting for interstellar reddening), so estimates of their effective temperatures are made by comparing spectral line profiles with those calculated from sophisticated models (Repolust et al. 2004); the resulting temperature estimates are typically accurate to 5 percent. Their luminosities are determined from their absolute magnitudes and bolometric corrections (again derived from models for the estimated temperature), but reliable absolute magnitudes are only available for O stars in clusters where distances are known from other techniques. For the majority of O stars, the absolute magnitudes are

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** For much of this discussion, B stars and Wolf-Rayet stars are also eligible. We concentrate here on the O stars for clarity.*

estimated from spectral classification calibrations (based upon those stars in clusters) that typically result in 25 percent distance errors, consequently resulting in luminosity errors approaching 50 percent. Thus, the observational HRD only loosely constrains modern evolutionary models for massive stars (Herrero et al. 2007).

Progress will clearly require better distance measurements from accurate trigonometric parallaxes. Most O stars are very distant, and the Hipparcos mission produced reliable distance measurements for just one or two cases (Schröder et al. 2004). In fact, of the 265 stars of spectral type O listed in the Hipparcos catalog (ESA 1997; van Leeuwen 2007), 75 have zero or negative parallaxes. None of the remaining 190 stars have parallax errors better than 10 percent, and only six have errors better than 20 percent (several of those are not dwarfs). Both Gaia and SIM Lite will dramatically change the situation, but in quite different ways (Figure 8-1).

Gaia can measure 1 percent parallaxes to only 33 of 378 stars in the Galactic O star Catalog (Maíz-Apellániz et al. 2004) because the majority of O stars are either brighter than V = 6 or too far away. On the other hand, SIM Lite will determine distances accurate to 1 percent for 259 of the 378 catalog stars,

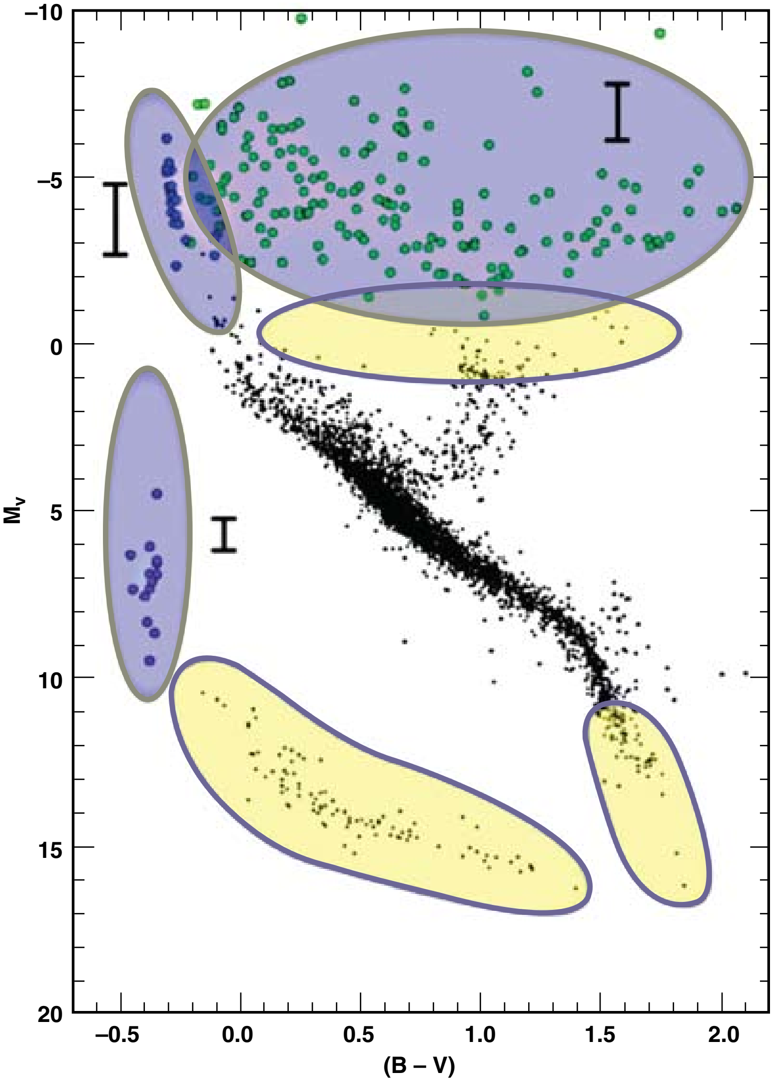

Figure 8-1. Characteristic regions of the HRD to be explored effectively by SIM Lite (blue) and Gaia (yellow), with error bars representative of current knowledge in the SIM Lite regions. Supergiants have been plotted using Hipparcos data for stars brighter than V = 6 with luminosity classes I or I/II. The mean parallax error is 37 percent for these stars. A representative sample of O stars is shown, although only six parallaxes are currently available with errors less than 20 percent; most errors are much larger. The 16 PNe central stars with parallaxes from Harris et al. (2007) are also shown, for which the average parallax error is 19 percent. Note that the representative error bars shown for O stars and PNe central stars are for the few stars for which any trigonometric parallax is known. Main sequence and giant branch data points represent stars from Hipparcos (van Leeuwen 2007 with updated 2008 data used) with distances less than 50 pc and errors less than 5 percent. Data for white dwarfs have been taken from Bergeron et al. (2001). Typically, objects extreme in the HRD are either very distant, very faint, or very bright. The precision and magnitude dynamic range of SIM Lite will reduce the error bars on those objects by factors of 10 to 20.

allowing us to select a larger and more astrophysically interesting group of massive stars that will allow us to test the predictions of evolutionary models. With 1 percent distances, we can accurately estimate ages of individual stars in young clusters and test models of star and cluster formation, find evidence of very faint, unresolved binary companions, and determine the ionizing flux from these stars that illuminates the surrounding ISM. Furthermore, accurate luminosities are crucial to testing the assumptions about interior structure, in particular the roles of rotation and meridional circulation (Ekström et al. 2008) that are important for the kinds of supernovae and compact remnants produced by massive stars. As a by-product, the distances to massive stars will reveal the spiral structure patterns in our quadrant of the Milky Way Galaxy.

8.2.2 Supergiants

SIM Lite can observe stars visible to the naked eye better than any other current or planned astrometric technique, including Gaia, which is not designed to measure stars brighter than V = 6. Found among the naked-eye stars are many famous supergiants, many of which are not in clusters, so fainter stars cannot be used as proxies for determining distances. With parallaxes accurate to 4 μas in wide-angle mode, SIM Lite will enable astronomers to (1) pinpoint supergiants' luminosities on the HRD, (2) understand how metallicities affect their positions, and (3) improve the wind-momentum luminosity relation (WLR) and flux-weighted gravity luminosity relation (FGLR) used to derive extragalactic distances. In addition, a bright-star parallax program with SIM Lite offers a fantastic public outreach opportunity not available to other efforts — astronomers will be able to tell anyone who might ask where the stars they can see are in our Galaxy.

Although Hipparcos did observe the brightest stars, many of the more distant supergiants have poorly determined distances. For example, among the 219 supergiants (luminosity classes I or I/II) brighter than V = 6 in the Hipparcos catalog, 167 have parallax errors greater than 10 percent and most are less than 1 kpc away (if the sizes of the Hipparcos parallaxes are correct). Some of these targets are among the famous stars seen in backyard skies the world over, including Alnitak (O9.5 Ia, $\pi = 4.43 \pm 0.64$ mas), Antares (M1.5 Iab, $\pi = 5.89 \pm 1.00$ mas), Betelgeuse (M2 Iab, $\pi = 6.55 \pm 0.83$ mas), Deneb (A2 Ia, $\pi = 2.31 \pm 0.32$ mas), and Rigel (B8 Iab, $\pi = 3.78 \pm 0.34$ mas), to name a few.* Improving the distance uncertainties from more than 10 percent to less than 1 percent would allow astronomers to understand the total flux contribution made by supergiants at various wavelengths, which has cascading effects on star-formation regions, dust creation, and the possible use of supergiants as standard candles for Galactic arm structure analyses. More specifically, knowing the distance to supergiants like Betelgeuse to 1 percent permits definitive checks on stellar radii in the late states of stellar evolution and what effects expanding layers have on binary star orbital migration and planetary habitable zone destruction.

Some supergiants have recently been used to determine distances to nearby galaxies through the WLR (Kudritzki et al. 1999) and the FGLR. These methodologies offer additional ways to determine extragalactic distances, at least to nearby galaxies. Kudritzki et al. (1999) selected 14 O/B-type supergiants to build the WLR, but only one of those stars has parallax determined to better than 10 percent. Therefore, the distances to these targets must be determined from their associations and presumed cluster memberships. On the other hand, the FGLR technique has been constructed using supergiants in the nearby galaxies NGC300 and NGC3621, which have distances determined using Cepheids (Freedman et al. 2001). In effect, no parallaxes have been used to develop these two relations, but this can be remedied

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** Parallax data are from the new Hipparcos reduction by van Leeuwen (2007). Betelgeuse has been recently observed by the Very Large Array at radio wavelengths, resulting in a trigonometric parallax of 5.07 ±1.10 mas (Harper et al. 2008).*

with SIM Lite. For example, a V = 6 supergiant observed for 10 s 100 times will yield a parallax accurate to 4 µas, which is a factor of 50 to 100 better than currently possible. Although it is unclear whether or not either methodology will ultimately prove viable as a distance ladder rung, what SIM Lite may reveal by measuring accurate distances to a large sample of supergiants is not entirely known — perhaps an entirely new type of standard candle will appear, once hundreds of supergiants are examined with SIM Lite's exquisite capabilities.

8.2.3 Planetary Nebulae Central Stars

Distances to planetary nebulae (PNe) are important for understanding the physics of the nebulae, the evolutionary state of the central stars (e.g., time since the ejection of material), and the space density and formation rate of PNe. At present, however, distances are notoriously uncertain, both in terms of systematic effects and for individual nebulae. Only 16 have measured trigonometric parallaxes (Benedict et al. 2003; Harris et al. 2007), and distances are large enough for most PNe that ground-based parallax errors (~300 µas) and HST errors (~200 µas) will preclude many more being measured until Gaia or SIM Lite. There are roughly 2000 PNe known in the Galaxy, many in and around the Galactic bulge that are particularly good targets for SIM Lite. They include a large variety of types, and understanding these different types adds scientific importance to getting accurate distances to many PNe. A goal might be to have distances with 10 percent errors or better to 300 PNe by the time Gaia and SIM Lite complete their observations.

Error estimates vs. magnitude from Lindegren et al. (2008) indicate that Gaia might be used to acquire parallaxes with 10 percent errors to about 190 PNe, using the Acker et al. (1992) catalog for central star magnitudes and estimated distances. SIM Lite can reach 10 percent error at a distance of 8 kpc at V = 16 in ~48 min total mission time (20 visits, 110 s integrations), which expands the target sample considerably. There are 170 PNe with $16 < V < 18$, for which Gaia is expected to have distance errors of 20 to 30 percent — these are potentially excellent targets for SIM Lite that would double the available sample of PNe with distance measurements accurate to 10 percent or better.

One additional product of SIM Lite astrometric data will be the identification of binary motion for PNe central stars. One theory of the origin of bipolar symmetry seen in many PNe argues that binary central stars are common. The accuracy of SIM Lite data and a planned cadence for SIM Lite visits will offer an advantage over Gaia for identifying (or placing upper limits on) binary motion for a sample of PNe central stars. A selected sample of bright (V ~ 15) central stars in bipolar PNe with an increased number of SIM Lite visits will provide constraints on the frequency of binaries: observing 140 bright PNe central stars 50 times each with SIM Lite can be accomplished in 140 hours of observing time. As a bonus, accurate proper motions for very faint PNe stars would permit the identification of halo objects and provide benchmarks for historical enrichment due to evolution of the oldest Galactic stars.

8.3 The Mass-Luminosity Relation

Mass is arguably the single most important characteristic of a star, as it determines a star's size and color, as well as how long it will live and what fuels it will burn. Knowing the masses of main sequence stars answers basic astrophysical questions such as: What is the biggest star? What is the smallest star? How is the mass of a stellar nursery partitioned into various types of stars? What is the mass content of the Galaxy and how does it evolve? To answer these and other fundamental questions, the ultimate goal is to determine masses to 1 percent accuracy, which allows us to challenge stellar models more severely than ever before.

The MLR's broad appeal is its applicability to many areas of astronomy. A reliable MLR lets us use a star's luminosity as a proxy for its mass, which is a valuable commodity in radial velocity, astrometric, cataclysmic binary, and extrasolar planet work. In the broader Galactic context, an accurate MLR provides benchmarks for comparisons to objects in stellar clusters, and allows us to estimate just how much of the "missing" mass is made up of the smallest stars. At the faint end of the stellar main sequence, the MLR is crucial for brown dwarf studies because measurement of a sufficiently small mass can demonstrate that a star is a bona fide brown dwarf. High-accuracy masses are needed because, as shown in Figure 8-2, the width of the main sequence on the MLR is 20 percent or more at a given luminosity. This is because, even though the individual stellar masses calculated to date are determined to 5 percent or better, they are of mixed pedigree in age and metallicity. SIM Lite will be a breakthrough mission for stellar mass determinations because it will be able to measure masses accurate to 1 percent in myriad environments and for a suite of different kinds of stars, as discussed below.

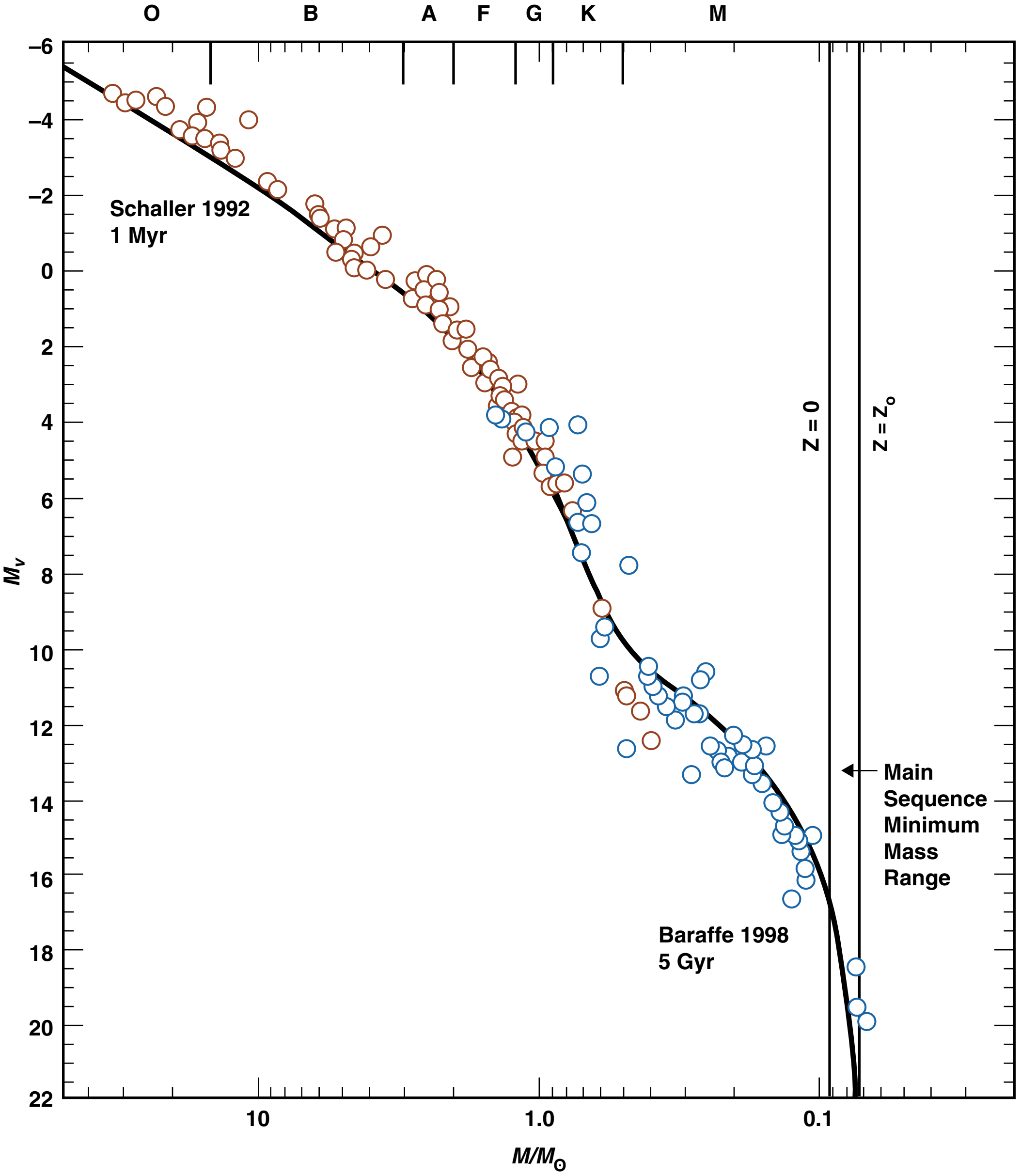

Figure 8-2. The mass-luminosity relation in 2008, using eclipsing binary data (open red points) from Andersen (1991) and others, supplemented with visual binary data (open blue points) from the SIM Science Team project, MASSIF, and others. Model curves for the MLR at the indicated ages and solar metallicity are shown, from Schaller et al. (1992) at high masses and Baraffe et al. (1998) at low masses. Note the spread in empirical mass determinations at a given luminosity throughout the main sequence, caused primarily by different ages and metallicities. SIM Lite's magnitude range from V = –1.5 to 20 enables binary star astrometry at the extremes of the MLR, including bright O dwarf and faint M dwarf binaries. In addition, most O binaries lie at great distances, requiring the high-fidelity parallaxes and resolving capability of SIM Lite's long baseline for accurate mass and luminosity measurements.

8.3.1 How SIM Lite Measures Masses

Typically, stellar mass estimates come from measurements of the orbital motions of binary stars. In particular, most accurate stellar masses have been inferred from studies of eclipsing spectroscopic binaries (Andersen 1991), but this method is severely limited for several important types of stars. At the highest masses, only a few known eclipsing systems contain O stars (Gies 2003), and many of these are interacting systems whose members may not be representative of single stars. At the lowest masses, stars are small, so few binaries eclipse and visual binaries must be used (Henry et al. 1999). Other rare but important types of evolved stars remain almost completely unmeasured.

To measure stellar masses, various combinations of imaging, interferometric, and radial velocity techniques are often used. Individual masses are typically computed via two paths: (1) by determining astrometrically the orbital inclination of the photocentric orbit of a double-lined spectroscopic binary (SB2), e.g., with SIM Lite, or (2) in the absence of high-quality radial velocities, resolving the system and measuring the relative orbit referenced to a grid of reference stars, also possible with SIM Lite. Resolution is particularly important for the MLR because the component luminosities must be measured to place the stars on the MLR (and on the HRD). To reach 1 percent mass accuracy for SB2s, an inclination precision of 0.2 percent is required for an orbit with $i = 45$ deg, assuming uncertainties in other orbital parameters do not dominate. For resolvable binaries, the minimum requirement for a 1 percent mass determination is a 0.33 percent distance measurement, which corresponds to 833 pc for SIM Lite's 4 μas wide-angle precision. Ideally, SB2s found in various target samples will be observed with SIM Lite to develop a well-stocked "toolbox" of MLRs determined for clusters of known age and metallicity; these MLRs will become the standards to which all stars can be compared.

The extraordinary abilities of SIM Lite allow us to both measure accurate distances to binary systems and resolve the systems into two stars. This allows us to pinpoint the locations of each component in the grid of reference stars and thereby determine individual masses. The diffraction limit of the SIM Lite 6-m interferometer operating at 0.55 μm is 10 mas. Given 80 spectral channels that can be used to compute fringe visibilities, we might expect to do somewhat better than the traditional diffraction limit, and simulations indicate that SIM Lite will be able to super-resolve systems with separations as small as 2 to 3 mas. SB2s that are resolved by SIM Lite will provide a wealth of redundancy in orbital elements, providing opportunities for increased mass precision and crosschecks.

For unresolved binaries, we can map the photocentric orbit to determine the all-important orbital inclination. For those that are not resolved, the SB2 orbits provide $M \sin^3(i)$, where i is the inclination angle (i.e., the angle between our line of sight and the normal to the orbital plane). The size of the photocentric orbit's semi-major axis is given by

$$\alpha = 19571 M_1^{1/3} (1 + q)^{-2/3} \; p^{2/3} \frac{q - f}{1 + f} d^{-1} \ \mu\text{as}$$

where M_1 is the mass of the primary star (in units of $M_\odot$), $q = M_2 / M_1$ is the mass ratio, p is the orbital period (days), $f = F_2 / F_1$ is the monochromatic flux ratio (related to the magnitude difference by $\log f = -0.4\Delta V$), and d is the distance to the binary (pc). For SB2s measured astrometrically, the shape of the photocentric orbit yields the inclination, and the measured photocentric orbit semi-major axis potentially provides redundant information on the flux ratio f and distance d. Single-lined systems (SB1s) can also be targeted, but components' locations on the MLR will be less precise because assumptions must be made about the flux and mass ratios, which are not determined explicitly for the components. Overall, with its combination of exquisitely accurate astrometry, faint-magnitude limit, and flexible scheduling, SIM Lite will allow us to measure masses for classes of objects for which accurate masses are scarce, such as pre-main-sequence stars, O stars, subdwarfs, and white dwarfs. These are representative examples of mass determinations that can be made with SIM Lite. Other classes of objects that might be targeted include stars with peculiar abundances, blue stragglers, subdwarf O and B (sdO/B) stars, X-ray binaries, cataclysmic binaries, and microquasars.

8.3.2 Star Clusters: MLRs for the Toolbox

Open-star 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 would 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. 1997). However, the Hyades MLR extends only from 2.4 to 0.8 $M_\odot$ with mass errors of 5 to 10 percent. 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 Lite's great accuracy is needed to reduce these errors to the 1 percent level needed for meaningful analyses.

The Hyades is a local, relatively old cluster. At the other age extreme is the Trapezium association in Orion. The Trapezium has been beyond the reach of precise trigonometric parallax measurements from the ground or with Hipparcos, with errors of 10 percent (translating to 20 percent luminosity errors and 30 percent mass errors, at best). Recently, VLBI work has provided a distance of 414 ± 7 pc (Menten et al. 2007), or an error of only 1.7 percent, at least for the four stars targeted in the Trapezium region. At roughly 10 times the distance of the Hyades, SIM Lite can measure hundreds of parallaxes for stars in the Orion Complex, while allowing accurate masses to be determined for selected binaries. The Hyades and Orion are but two of several fundamental clusters within the reach of SIM Lite, some of which are listed in Table 8-2 in order of their estimated distances.

Table 8-2. Binary systems, observable by SIM Lite, in fundamental stellar clusters containing binaries with orbital periods of 2.5 years. Binary systems in which component masses can be measured accurately (~1 percent) by Gaia are shaded in yellow. Those that are only reachable by SIM Lite for 1 percent masses are shaded in blue. SIM's high accuracy, especially at faint magnitudes, brings a wealth of clusters into reach for accurate masses. Particularly noteworthy are the Orion and M67 clusters, which span a factor of 1000 in age.

			A Star Primary	G Star Secondary	K Star Primary	M Star Secondary
Mass, $M_\odot$			1.5	1.0	0.7	0.4
M_V			3.0	5.0	7.5	11.0
Cluster	**Est Dist, pc**	**Est Age, Myr**	**V mag Pri+Sec**	**Semi-Major Axes Rel/Phot, mas**	**V mag Pri+Sec**	**Semi-Major Axes Rel/Phot, mas**
Hyades	45	630	6.3 + 8.3	55.6 / 14.6	10.8 + 14.3	42.3 / 13.7
TW Hydrae	55	10	6.7 + 8.7	45.5 / 12.0	11.2 + 14.7	34.6 / 11.2
Pleiades	135	80	8.7 + 10.7	18.5 / 4.9	13.2 + 16.7	14.1 / 4..6
IC2602	160	20	9.0 + 11.0	15.6 / 4.1	13.5 + 17.0	11.9 / 3.9
IC2391	160	40	9.0 + 11.0	15.6 / 4.1	13.5 + 17.0	11.9 / 3.9
NGC6774	200	2000	9.5 + 11.5	12.5 / 3.3	14.0 + 17.5	9.5 / 3.1
M7	240	220	9.9 + 11.9	10.4 / 2.7	14.4 + 17.9	7.9 / 2.6
NGC0752	360	2700	10.8 + 12.8	6.9 / 1.8	15.3 + 18.8	5.3 / 1.7
M34	400	250	11.0 + 13.0	6.3 / 1.6	15.5 + 19.0	4.8 / 1.5
Orion	450	5	11.3 + 13.3	5.6 / 1.5	15.8 + 19.3	4.2 / 1.4
NGC3532	500	300	11.5 + 13.5	5.0 / 1.3	16.0 + 19.5	3.8 / 1.2
M35	700	150	12.2 + 14.2	3.6 / 0.9	16.7 + 20.2	2.7 / 0.9
M67	800	5000	—	—	17.0 + 20.5	2.4 / 0.8

The Hyades cluster, several stars in the Pleiades, and a few stars in TW Hydrae currently have reliable parallaxes. Gaia will provide parallaxes good to 1 percent out to 1.2 kpc. Assuming a large enough number of observations and sufficient orbital coverage, Gaia should also determine photocentric (unresolved) binary orbits to similar precision. To reach 1 percent precision in the masses, however, both the parallax and orbital semi-major axis must be known to 0.33 percent because the semi-major axis in AU enters as the cube when determining masses using Kepler's Law.*

In Table 8-2, we outline the characteristics of two hypothetical binary pairs in several clusters of interest, including an A/G pair and a K/M pair (no A stars remain in M67). In each case, we assume orbital periods of 2.5 years to allow both Gaia and SIM Lite to map each system through two complete orbits. We assume identical parallax and semi-major axis errors for a binary observed with a given mission, with Gaia errors of 8 to 55 μas for V = 6 to 17 and 4 μas uniformly for SIM Lite. For SIM Lite, fainter targets require longer observing times, but 4 μas can be reached on a V = 17 target with 32 hours of mission time. As a baseline, we assume no errors in orbital period and fractional mass, as well as no error in translation from a photocentric orbit to a relative orbit.

In the Hyades, Gaia can measure masses to 0.1 percent for both the A/G and K/M pairs, while SIM Lite produces errors half as large. In the old cluster NGC6774 at 200 pc, Gaia's mass errors for the A/G binary are 0.5 percent and for the K/M binary 0.9 percent, again assuming no errors other than those in parallax and photocentric semi-major axis. SIM Lite measures masses with errors of 0.3 percent for both pairs. Gaia's mass precision deteriorates beyond 200 pc because the parallax and photocentric orbit errors become significant, and the K/M binaries become faint. In the crucial Orion complex at 450 pc, mass errors for the pairs are 1.2 percent and 5.2 percent for Gaia, but only 0.6 percent in both cases for SIM Lite.

An important binary in Orion illustrates SIM Lite's broad power clearly: θ^1 Ori C is an O7V + B2V pair with an orbital period of 26 ±13 years and semi-major axis of 41 ±14 mas (Patience et al. 2008). With V = 5.1, Gaia cannot observe this important system because it is too bright, while SIM Lite can determine the parallax to 0.2 percent (and luminosity to 0.4 percent), resolve the pair easily, and map a portion of the orbit during its five-year mission.

Thus, beyond about 200 pc, SIM Lite can maintain the high-precision mass determinations necessary to challenge theoretical models throughout the main sequence, while Gaia cannot. Of special significance is that SIM Lite can resolve binaries with separations of a few mas and to differences in component fluxes of at least three magnitudes, so it can provide both the separations and luminosities of the components for all of the A/G pairs listed in Table 8-2 as well as most of the K/M pairs, none of which can be resolved with Gaia. Because of SIM Lite's flexible schedule, observations can also be timed to provide coverage near crucial periastron passages to provide the most accurate masses possible. Of special interest is SIM Lite's ability to produce a reliable MLR for ancient M67, whose constituent stars are all the same age and metallicity as the Sun. Overall, what is particularly compelling about this work is that the clusters span a range of 1000 in age, thereby providing a beautiful framework within which to study many aspects of stellar evolution once accurate distances and masses are available from SIM Lite.

** For the numbers presented in Table 8-2, we provide the most straightforward example, assuming a dynamical orbit determined entirely by SIM Lite and resolution of the binary by SIM Lite or another technique. Of course, by combining astrometric and radial velocity data, some of the astrometric constraints can be relaxed. In practice, there is a complicated interplay between orbital elements (inclination, for example) determined using a combination of techniques to derive orbital period, relative semi-major axis on the sky, parallax, proper motion, and fractional mass necessary for individual component mass determinations. A complete discussion of these factors is beyond the scope of this chapter.*

8.3.3 Pre-Main Sequence Stars

With the exception of solar-mass objects, evolution models of stars from birth to the zero-age main sequence are poorly calibrated (Schaefer et al. 2008 and references therein). Binaries in star formation regions provide an opportunity to determine precise dynamical masses in low-mass, young star systems (e.g., Prato et al. 2002; Hillenbrand and White 2004). Fewer than 100 pre-main-sequence (PMS) spectroscopic binaries (SBs) are currently known (Melo et al. 2001), and even fewer eclipsing PMS SBs have been identified (Stassun et al. 2007). Models of young star evolution would be revolutionized by mass determinations of a few dozen binaries among the youngest T Tauri star populations that are accurate to a few percent, via SIM Lite.

Unfortunately, only a small handful of young stars are at once close enough to determine precise radial velocities of the components and yet widely separated and bright enough to be accessible to ground-based interferometry (Boden et al. 2007; Schaefer et al. 2008). SIM Lite is the only facility that has the capacity to accurately determine the orbit of the photocenter of the shortest period (<100 days) T Tauri star SBs, providing the system inclinations and, hence, absolute component masses to the required few percent precision for meaningful calibration of evolutionary tracks.

About three dozen PMS SB1 and SB2 systems are currently known with P <100 days, including many in the Taurus, Ophiuchus, and TW Hya regions within 150 pc. Gaia will do well on the brighter systems, but only SIM Lite can provide the masses for PMS systems of low mass, where young star models show the greatest variations. Finally, a significant advantage of SIM Lite over other techniques for PMS binaries, many of which do not provide accurate radial velocity measurements, is its ability to resolve binaries with separations of a few mas, thereby placing both components in a grid of reference stars so that individual masses can be measured.

8.3.4 Massive Stars

Although O stars are rare, as a group they are known to contain many binaries, with a multiplicity fraction of 75 percent for those found in clusters or associations (Mason et al. 1998). Many of those that are found to be SB2s also eclipse, which would be ideal for mass determinations except that such binaries are usually so close that they may have physically interacted in the past. Thus, mass estimates for such systems may tell us more about the evolutionary mass exchange histories of binaries rather than providing fundamental data to calibrate the properties of stars in general. For non-interacting, non-eclipsing O star binaries, masses are determined by supplementing an SB2 orbit with a precisely determined orbital inclination, or by resolving the binary and finding the shape of the orbit. Because O stars are rare and consequently distant, such measurements will require the precise astrometric and interferometric measurements of SIM Lite.

There are many spectroscopic binaries containing massive stars where observations of the photocentric orbit would lead directly to masses. One example is the system CygOB2 #8A, which consists of O5.5 I and O6 stars in a 22-day orbit (De Becker et al. 2004). The system resides in the Cyg OB2 association at a distance of 1.5 kpc, and the expected photocenter semi-major axis is predicted to be 59 μas, much larger than the typical single observation position error of ≈16 μas for wide-angle measurements with SIM Lite. A more challenging object is HD93205 in the Carina Nebula region at a distance of 2.6 kpc. This is a 6 d binary consisting of O3 V and O8 V stars (Antokhina et al. 2000), and the maximum photocenter motion will be in the range of 9 to16 μas (depending on the adopted flux ratio). SIM Lite will be uniquely suited to obtain the orbital inclination and distance of this system and to peg the mass of a star at the top of the main sequence (~45 $M_\odot$ for an O3 V star).

SIM Lite will also provide insight into the evolutionary descendants of massive stars. The most massive stars develop strong stellar winds early in life that can remove their outer hydrogen layers and create a helium-rich Wolf-Rayet (WR) star. SIM Lite positional measurements of the binary WR 22 (WN7 + O9 III; Schweickhardt et al. 1999) will show a maximum positional displacement of 45 µas over its 80-day orbit and will lead to secure mass estimates for both stars (the mass of the WR star is ~55 ±7 $M_{\odot}$).

SIM Lite will also play a key role in determining masses of low-luminosity companions of massive stars. Many interacting binaries experience mass and angular momentum transfer that lead to the spin up of the mass-gainer and the loss of the donor star's envelope. Eventually, the donor may appear as a stripped-down helium star or white dwarf. The nearby B7 V star Regulus is one example of a rapid rotator that was recently found to have a faint binary companion (probably a low-mass white dwarf; Gies et al. 2008). SIM Lite observations of the photocenter motion of Regulus may reveal orbital excursions as large as 1200 µas, and these would lead directly to the mass of the faint companion (note that Gaia cannot observe Regulus at V = 1.4).

Finally, we know that many massive binaries are also members of triple or higher multiplicity systems, and with its resolving capabilities, SIM Lite can give us the complete picture of both wide (mas) and close (µas) members of hierarchical systems. Ultimately, SIM Lite will finally be able to tell astronomers what the upper mass limit is for a star.

8.3.5 Subdwarfs

Subdwarfs are Galactic fossils that presumably comprise the bulk of the halo, and are crucial touchstones of the star-formation and metal-enrichment histories of the Milky Way. The local dearth of subdwarfs and their intrinsic faintness make them difficult to characterize, unlike their disk counterparts. Because of these challenges, their masses are barely measured, but would be of great use in studies of the Galactic halo, globular clusters, and low-metallicity stars in general.

The MLR for main-sequence stars has been studied in detail for decades, but constructing the MLR for the neglected metal-poor stars has barely begun. There are currently only three subdwarf systems (defined here to have [Fe/H] ≤ –0.5) with mass measurements: µ Cas AB (Drummond et al. 1995) with [Fe/H] = –0.71 (Karaali et al. 2003); HD157948 AB with [Fe/H] = –0.5 (Horch et al. 2005); and HD195987 AB with [Fe/H] = –0.5 (Torres et al. 2002). Clearly, there remains much work to do in calibrating the empirical MLR of metal-poor subdwarfs.

Utilizing the unique combination of precise astrometry and high-resolution capability of SIM Lite, we can expect to map many more subdwarf orbits. Prime examples are 15 F- and G-type low-metallicity (–2.5 ≤ [Fe/H] < –0.5) SB2 systems from Goldberg et al. (2002) that have $a \sin(i)$ > 1.0 mas and orbital periods less than four years. Roughly 100 additional SB1 systems from Latham et al. (2002) with period less than three years could also be targeted by SIM Lite to increase the total number of resolved binaries. Because of the combination of faint magnitudes and small separations, no other current astrometric technique can resolve either set of binaries, but SIM Lite can. A typical F/G binary pair with orbital period 2.5 years and semi-major axis 22 mas would yield masses with errors less than 1 percent, assuming SIM Lite can measure the semi-major axis to 0.1 mas. To expand dynamical mass measurements to lower masses, we need to survey the ~120 nearby K- and M-type subdwarfs within 60 pc. Optical speckle surveys (Jao et al. 2008, submitted) fail to detect binaries with appropriate separations for mass determinations because at the comparatively large distances of the subdwarfs, optical speckle cannot reach to the mas separations needed for short (less than a decade) orbits. Gaia should reveal which subdwarfs have photocentric orbits appropriate for mass determinations, but only SIM Lite can resolve the systems and provide the high-fidelity mass measurements needed to test theoretical models for low-metallicity stars.

8.3.6 White Dwarfs

White dwarf (WD) research has far-reaching implications in diverse astronomical fields, from cosmology to Galactic halo populations to nearby star studies. Gaia will undoubtedly reveal many systems containing WDs that are appropriate for mass determinations, but SIM Lite's ability to measure masses with exquisite precision reveals a niche that is unique to SIM Lite — understanding the theoretical mass-radius relation for WDs. From the youngest WDs found as central stars in PNe to the oldest WDs from the halo, SIM Lite's reach brings unusual objects into reach for mass determinations of this class of objects with various compositions and ages.

Nearly every aspect of WD research relies on the theoretical mass-radius relation for WDs. This relationship depends on the internal composition of the WD, whether it is a pure or mixed combination of He, C, N, Ne, or Mg. Ideally, WD masses need to be known to 1 percent (or better) to stress test the mass-radius relation to reveal the true chemical makeup of WDs, and permit us to discriminate, for example, between different hydrogen envelope masses (Jordan 2007).

To date, empirical masses to support the theoretical mass-radius relationship are severely limited — only three WDs have dynamical mass measurements known to better than 5 percent: Sirius B, Procyon B, and 40 Eri B (Provencal et al. 2002). Other WDs with masses, such as the remaining 18 WDs that populate the mass-radius relation in Figure 13 of Provencal et al. (2002), have masses gleaned from gravitational redshift studies of common proper motion systems (in which a companion is used to determine systemic parameters) or have spectroscopically inferred masses. In general, such mass determinations are rather poorly constrained, with errors of 10 percent or more.

It is important to obtain precise dynamical masses for a much larger number of WDs to better test and validate the theoretical mass-radius relation that is vital to WD modeling. Empirical determinations of dynamical masses in visual, spectroscopic, or interferometric binaries for WDs will better constrain the relative proportions of internal compositions of WDs found in the solar neighborhood. This information may then be applied to pulsating ZZ Ceti stars, whose pulsation modes are used to determine details of the internal structure.

A combined Gaia (for detection) and SIM Lite (for resolution and high precision) effort will likely provide a wealth of additional WD masses that could be used to map out the mass-radius relation for WDs. Through ongoing studies of double-degenerate systems with Hubble Space Telescope's fine-guidance sensors, eight systems have already been identified that might provide masses accurate to 1 percent when examined with SIM Lite. At separations of a few to tens of mas, these systems, as well as many more detected by Gaia, can be resolved by SIM Lite. Hence, SIM Lite's measurements will play a crucial role in populating the mass-radius diagram with multiple empirical checks of the theoretical mass-radius relation. These checks will reveal new insights into the internal structures of WDs and answer questions about WD compositions that have long eluded astronomers.

8.4 Summary

SIM Lite and Gaia are clearly complementary observatories for studies of stellar astrophysics. As shown in Figure 8-1, with its breadth of coverage Gaia will effectively complete our understanding of the HRD for common stars, while SIM Lite will target the rare supergiants, O stars, and PNe central stars. Other truly rare stellar phenomena, such as X-ray binaries and their precursors, will require the laser accuracy of SIM Lite simply because they are not common enough to have nearby representatives. SIM Lite's exquisite accuracy is also crucial to mapping the MLR in fundamental stellar clusters such as Orion and M67, where individual masses can be measured to 1 percent only by SIM Lite. Binaries containing pre-main sequence stars, O stars, subdwarfs, and white dwarfs are superb targets for SIM

Lite, which can not only measure their distances and orbits but resolve the systems into components to provide individual masses — there is much to be said for mapping a binary's orbit and resolving the system with the same instrument to minimize systematic translation errors between observing techniques. Finally, there is little doubt that Gaia will be a pathfinder mission for SIM Lite, much like the Palomar Schmidt was for the 200-inch telescope. New and extraordinary objects will be revealed by Gaia, and breakthroughs in stellar astrophysics will be made when SIM Lite's μas astrometry capabilities are applied.

References

Acker, A., Ochsenbein, F., Stenholm, B., Tylenda, R., Marcout, J., and Schohn, C., 1992, Strasbourg-ESO Catalogue of Galactic Planetary Nebulae.

Andersen, J., 1991, A&A Reviews, 3, 91.

Antokhina, E. A., Moffat, A. F. J., Antokhin, I. I., Bertrand, J.-F., and Lamontagne, R., 2000, ApJ, 529, 463.

Baraffe, I., Chabrier, G., Allard, F., and Hauschildt, P. H., 1998, A&A, 337, 403.

Benedict, G. F. et al., 2002, AJ, 124, 1695.

Benedict, G. F. et al., 2003, AJ, 126, 2549.

Benedict, G. F. et al., 2007, AJ, 133, 1810.

Bergeron, P., Leggett, S. K., and Ruiz, M. T., 2001, ApJS, 133, 413.

Boden, A. F. et al., 2007, ApJ, 670, 1214.

De Becker, M., Rauw, G., and Manfroid, J., 2004, A&A, 424, L39.

Drummond, J. D. et al., 1995, ApJ, 450, 380.

ESA, 1997, VizieR Online Data Catalog, 1239, 0.

Ekström, S., Meynet, G., Maeder, A., and Barblan, F., 2008, A&A, 478, 467.

Gies, D. R., 2003, in A Massive Star Odyssey: From Main Sequence to Supernova (Proc. IAU Symp. 212), ed. van der Hucht, K., Herrero, A., and Esteban, C. (San Francisco: ASP), 91.

Gies, D. R. et al., 2008, ApJ, 682, L117.

Goldberg, D. et al., 2002, AJ, 124, 1132.

Harper, G. M., Brown, A., and Guinan, E. F., 2008, AJ, 135, 1430.

Harris, H. C. et al., 2007, AJ, 133, 631.

Henry, T. J. et al., 2006, AJ, 132, 2360.

Henry, T. J. et al., 1999, ApJ, 512, 864.

Herrero, A., Simon-Díaz, S., Najarro, F., and Ribas, I., 2007, in Massive Stars in Interacting Binaries (ASP Conf. Ser. 367), ed. St-Louis, N. and Moffat, A. F. J. (San Francisco: ASP), 67.

Hillenbrand, L. A. and White, R. J., 2004, ApJ, 604, 741.

Horch, E. P. et al., 2005, Astrometry in the Age of the Next Generation of Large Telescopes, ASP Conference Series, vol. 338, Proceedings of a meeting held 18–20 October 2004 at Lowell Observatory, Flagstaff, Arizona, USA. Ed. Seidelmann, P. K. and Monet, A. K. B., San Francisco: Astronomical Society of the Pacific, p. 90.

Jordan, S., 2007, 15th European Workshop on White Dwarfs, 372, 169.

Karaali, S. et al., 2003, MNRAS, 343, Issue 3, 1013.

Kudritzki, R. P. et al., 1999, A&A, 350, 970.

Latham, D. W. et al., 2002, AJ, 124, 1144.

Lindegren, L. et al. 2008, IAU Symposium 248, 217.

Mason, B. D., Gies, D. R., Hartkopf, W. I., Bagnuolo, W. G., Jr., ten Brummelaar, T., and McAlister, H. A., 1998, AJ, 115, 821.

Maz-Apellaniz, J., Walborn, N. R., Galue, H. A., and Wei, L. H., 2004, ApJS, 151, 103.

Melo, C. H. F., Covino, E., Alcala, J. M., and Torres, G., 2001, A&A, 378, 898.

Menten, K. M., Reid, M. J., Forbrich, J., and Brunthaler, A., 2007, A&A, 474, 515.

Patience, J. et al., 2008, ApJ, 674, L97.

Prato, L., Simon, M., Mazeh, T., McLean, I. S., Norman, D., and Zucker, S., 2002, ApJ, 569, 863.

Provencal, J. L., Shipman, H. L., Koester, D., Wesemael, F., and Bergeron, P. 2002, ApJ, 568, 324.

Repolust, T., Puls, J., and Herrero, A., 2004, A&A, 415, 349.

Schaefer, G. H., Simon, M., Prato, L., and Barman, T., 2008, AJ, 135, 1659.

Schaller, G., Schaerer, D., Meynet, G., and Maeder, A., 1992, A&AS, 96, 269.

Schröder, S. E., Kaper, L., Lamers, H. J. G. L. M., and Brown, A. G. A., 2004, A&A, 428, 149.

Schweickhardt, J., Schmutz, W., Stahl, O., Szeifert, Th., and Wolf, B., 1999, A&A, 347, 127.

Stassun, K. G., Mathieu, R. D., and Valenti, J. A., 2007, ApJ, 664, 1154.

Torres, G., Boden, A. F., Latham, D. W., Pan, M., and Stefanik, R. P., 2002, AJ, 124, 1716.

Torres, G., Stefanik, R. P., and Latham, D. W., 1997, ApJ, 485, 167.

van Altena, W. F., Lee, J. T. and Hoffeit, E. D., 1995, Catalogue of Trigonometric Parallaxes.

van Leeuwen, F., 2007, Hipparcos, the New Reduction of the Raw Data, Astrophysics and Space Sciences Library, 350, Springer, and updated data via Vizier in 2008.