New Frontiers in Binary Stars:
Science at High Angular Resolution

Gail Schaefer (Georgia State Univ.), **Tom Armstrong** (NRL), **Chad Bender** (NRL), **Michelle Creech-Eakman** (New Mexico Tech.), **Francis Fekel** (Tennessee State Univ.), **Otto Franz** (Lowell), **William Hartkopf** (USNO), **Donald Hutter** (USNO), **Brian D. Mason** (USNO), **John Monnier** (Univ. of Michigan), **Matthew Muterspaugh** (Tennessee State Univ.), **Lisa Prato** (Lowell), **Stephen Ridgway** (NOAO), **Michal Simon** (Stony Brook University), **Theo ten Brummelaar** (Georgia State Univ.), **Lawrence Wasserman** (Lowell), and **Ming Zhao** (Univ. of Michigan)

Contact Information:
Gail Schaefer
The CHARA Array of Georgia State University
Mount Wilson Observatory
Mount Wilson, CA 91023
626-796-5405
schaefer@chara-array.org

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE **New Frontiers in Binary Stars: Science at High Angular Resolution**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **The CHARA Array of Georgia State University,Mount Wilson Observatory,Mount Wilson,CA,91023**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Abstract

The mass of a star determines how it evolves throughout its lifetime from beginning to end. Understanding the fundamental relationships between stellar mass, luminosity, and radius over a range of metallicities from the current solar values to the extremely low metallicities representative of the early universe is essential to the study of stellar astrophysics. This requires measuring high precision masses for stars over a wide range of evolutionary stages. Such masses can be obtained through mapping the three-dimensional orbits of binary stars. Continuing to apply this technique to shorter period binaries and to fainter or more distant systems over the next decade requires continued access to the highest angular resolution measurements, such as those achieved through long baseline optical/infrared interferometry.

1. Binaries as Tools for Measuring Stellar Masses

Binary stars are one of the most effective tools for measuring accurate stellar masses. Measuring dynamical masses requires information about the period, shape, orientation, and physical scale of the orbit. Visual binaries provide the geometry and dynamics of the orbit, but lack information that define the physical size. On the other hand, radial-velocity curves of spectroscopic binaries have the advantage of providing a physical scale, but do not provide the orbital inclination. However, if a spectroscopic binary eclipses, the inclination can be inferred from light-curve data. Alternatively, a combination of radial-velocity and visual orbit data provides a complete assessment of the orbital parameters, yielding masses of the individual stars. For these visual/spectroscopic pairs, the distance ("orbital parallax") can be measured from comparing the physical and angular scales.

Each observational technique has its limitations. The geometry of eclipses favors the detection of close, interacting systems in which common-envelope evolutionary effects make it hard to generalize the results to single-star evolution, although they present unique laboratories to study mass and momentum transfer and tidal distortions. Speckle interferometry and adaptive optics have been quite successful in resolving detached spectroscopic binaries, but the period/separation regimes accessible to these techniques have limited overlap. Spectroscopic pairs tend to be close to the resolution limit for a single-aperture telescope, so astrometric accuracy is decreased. At the same time, periods of visual pairs tend to be longer so that the velocity separations are small, resulting in blended lines, so the spectroscopic elements suffer in quality. As a result, the number of speckle/spectroscopic pairs with well-determined masses is small.

The past twenty years have seen accelerating progress in extending mass determinations as long-baseline optical/IR interferometry (LBOI) has produced visual orbits of many double-lined spectroscopic binaries. LBOI has the ability to resolve even short period binaries and often results in orbits with precisions in the dynamical masses of better than $\sim 1\%$ (e.g. Hummel et al. 2001; Boden et al. 2005; see Figure 1). Currently, roughly 100 stellar masses are known at this level of precision, obtained primarily through radial-velocity studies of eclipsing binaries and combining radial-velocity curves of non-eclipsing binaries with interferometric visual orbits. These visual orbits are often measured at such high precision that the uncertainty in the masses is frequently dominated by the radial-velocity data.

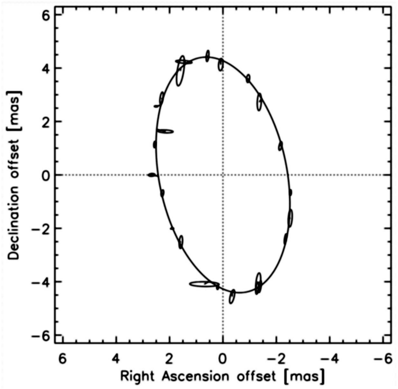

Figure 1: Visual orbit of the double-lined spectroscopic binary Omicron Leonis measured with Navy Prototype Optical Interferometer, the Mark III Stellar Interferometer, and the Palomar Testbed Interferometer (from Hummel et al. 2001). With a period of 14-days and a semi-major axis of only 4.46 milli-arcsec (mas), these results show the exquisite angular resolution achieved by long-baseline optical/IR interferometry.

To partially remedy that situation, dozens of bright field spectroscopic binaries are being re-observed (e.g. Fekel & Tomkin 2004; Tomkin & Fekel 2006) to provide significantly improved spectroscopic orbits, often for systems with different component mass ratios or in different evolutionary states. Additionally, high resolution infrared spectrometers have also aided in measuring radial velocities in low mass-ratio systems. Binaries composed of stars with unequal masses will have a secondary to primary flux ratio that increases toward longer wavelengths, making the companion easier to detect in the infrared (e.g. Prato et al. 2002; Mazeh et al. 2002, 2003). Probing to very small mass ratios can be accomplished by precision closure phase measurements obtained with LBOI that are likely to resolve high contrast companions at small separations (Zhao et al. 2008).

Over the next decade, LBOI holds the promise of significantly increasing the number of stars over a wide variety of evolutionary stages for which we will measure high precision stellar masses. This will allow us to address a number of fundamental questions: How does metallicity affect the mass-luminosity relation? What can a precisely calibrated initial mass function and angular momentum distribution within multiple systems tell us about competing theories of star formation? What are the age spreads and spatial extent of nearby star forming regions, and what are their implications for the dissipation of circumstellar disks and the stages at which planets form? How can we better calibrate the theoretical isochrones that are used to study age distributions of stellar populations and to investigate their star formation histories?

2. Astrophysics of Main Sequence Stars

The fundamental relationship between the mass and luminosity of a star allows astronomers to study the history of star formation across a variety of stellar populations in the Galaxy and in extragalactic clusters. While often plotted and understood as a simple function, the mass-luminosity relation (MLR) is in reality not a line, but rather a band of varying width due to metallicity and evolutionary effects. Differentiating these effects requires masses at the 1% level or better. Our knowledge of stellar masses at both the high- and low-mass ends of the main sequence remains incomplete. At the high mass end, the reduced number of narrow spectral lines for stars earlier than mid-F makes obtaining radial-velocity data of the precision needed to reach 1% accuracy in the masses difficult. Additionally, the most massive stars (mid-B and earlier) that enrich the Galactic environment via supernovae are typically located at large distances, resulting in orbits with small angular separations (e.g. Mason et al. 2009). LBOI has the potential to spatially resolve many more of these high mass stellar systems. At the lower end of the main sequence, masses of stars are poorly known primarily because of their faintness. M-dwarfs form a majority of stars in the Galaxy and could provide a strong test of evolutionary models because of the high dependence between luminosity and age at low masses (e.g. Henry et al. 1999). Improved sensitivity of interferometric arrays will allow access to a larger number of these fainter, lower mass binaries.

In addition to mass, the fundamental quantities of luminosity and radius can often be extracted from high angular resolution binary data. The angular resolutions available from current interferometers and expected from those under development are sufficient to measure the radii of solar-type stars out to ∼100 pc, while the orbital parallax and apparent magnitude produce the luminosity.

3. Open Clusters

Dynamical observations of binary stars in clusters will directly address many fundamental problems in star formation and stellar evolution. Clusters provide well defined stellar populations, with memberships that have a common formation history and evolution. LBOI observations of cluster members, combined with infrared spectroscopy (e.g. Bender & Simon 2008), will measure true, dynamical masses for a large sample of co-evolved stars. Such results lead directly to a localized initial mass function for star formation in the cluster, that is independent of theoretical models and does not suffer from the binary contamination present in photometric surveys (Bonnell et al. 2007; Kroupa 2002). The distributions of orbital parameters, masses, and mass ratios from such a survey can distinguish between the effects of fragmentation, dynamical interaction, and accretion in theories of binary star formation (Ballesteros-Paredes et al. 2007). Additionally, the orbital parallax measurements that result from full dynamical orbits provide the cluster distance and, when combined with a mass-luminosity relationship, the age (e.g. Armstrong et al. 2006). Current interferometers can observe both long and short period binaries in nearby clusters such as the Hyades, where such observations are currently underway. Moderate technological improvements in angular resolution and brightness sensitivity will allow observations of binaries over a large range of stellar masses in more distant clusters, such as the Pleiades, the Praesepe, and α Per.

4. Pre-Main Sequence Stars

Masses and ages of pre-main sequence (PMS) stars are commonly determined from the placement of stars relative to evolutionary tracks on an H-R diagram. However, different sets of theoretical tracks predict a large range of possible stellar masses at young, PMS ages (Simon 2001, Hillenbrand & White 2004, Mathieu et al. 2007). These discrepancies arise from the treatment of interior convection, atmospheric opacities, and initial conditions (e.g. Baraffe et al. 2002). As a result of the uncertainties in the tracks, the mass spectrum of stars produced in a star-forming region, the distribution of masses in binaries, and the region's star-formation history are imprecisely known. Dynamical masses of PMS binaries provide empirical data for calibrating the evolutionary tracks at young ages.

The youngest PMS stars (< a few MY) are located at distances greater than 100 pc. At these distances, short-period binaries present a challenge to resolve spatially. It is only recently that LBOI has achieved the sensitivity to begin resolving the orbits of PMS double-lined spectroscopic binaries (Boden et al. 2005, 2007; Schaefer et al. 2008). Overall, HIPPARCOS parallaxes for stars in nearby star forming regions yield distances to at best 10% precision, a level that is not particularly useful. The value of precise distance determination is shown by the few precise measurements of parallaxes now available from radio interferometry (e.g. Loinard et al. 2008) and the orbital parallaxes of the spatially resolved spectroscopic binaries. Binaries are a common product of star formation in the relatively low density regions such as in Taurus and Ophiuchus. Orbital parallaxes of suitable binaries will yield precise measurements of their luminosities, estimates of the spread of ages of formation (because the binary components are expected to be nearly coeval), and studies of the structure of the star forming region.

5. Post-Main Sequence Evolution

Using LBOI to resolve orbits of spectroscopic binaries with good metallicity characterization and where one member of the binary is evolving off the main-sequence (luminosity class IV), places a very strong constraint on the age of the system (Boden et al. 2000). This is much like studying turn-off points in clusters, but can now be done for individual binary systems, deriving masses at the 1% level and subsequently used to constrain isochrone models at particular metallicities (Torres et al. 2002).

The formation and equation of state of compact objects can also be investigated through high angular resolution studies. For instance, white dwarf companions are often difficult to detect because of the large flux difference relative to the brighter star. Precision closure phase measurements using LBOI have the potential to detect close companions in high contrast binaries. The development of space-based missions that achieve micro-arcsecond astrometric precision will measure astrometric signatures of the companion stars of neutron stars and black holes, and determine the masses of these compact objects.

6. Population II Binaries

Population II stars are of fundamental astrophysical importance because they comprise the membership of halo globular clusters and dwarf spheroidal galaxies, dynamically trace the Galactic components of the Milky Way, are progenitors of Type Ia supernovae, and provide footprints of the material from which early generations of stars in our Galaxy formed. As such, they are key bridges to our understanding of galaxy formation and evolution, and are a crucial link in the cosmic distance ladder. Furthermore, the stellar mass-luminosity relation (MLR) has been determined on the basis of primarily, but not purely, population I stars (e.g. Popper 1980; Henry et al. 1999; Gratton et al. 2004), hence the scatter resulting from a metallicity gradient is uncalibrated. A pure population II MLR has not yet been derived. Our incomplete knowledge of the population II is a direct result of the greater difficulty of observing the distant field halo stars and halo globular clusters.

The vast majority of population II systems are more distant than population I disk stars (e.g. Carney & Latham 1987). As a consequence, few binary population II binaries were initially identified (e.g. Gunn & Griffin 1979), although Latham et al. (2002 and references therein) later confirmed that population II binary frequencies are equivalent to population I frequencies. In spite of the inherent challenges, such as weak spectral lines, dozens of population II spectroscopic binaries have now been characterized. Recent and on-going observations and analysis provide double-lined radial velocity data for these systems (e.g., Latham et al. 1988; Goldberg et al. 2002; Torres et al. 2002; Heasley et al. 2009). However, in order to determine a population II MLR and to otherwise accurately characterize population II stars, absolute masses and precise distances are required, necessitating orbital solutions. Although some ground-based and space-based orbits have been obtained (e.g., Horch et al. 2006), even a moderate improvement in ground-based interferometric sensitivities (V$\sim$9 mag) could, within the decade, increase the sample of population II stars with well-derived absolute masses and distances by an order of magnitude.

7. Higher-Order Multiple Systems

The study of multiple systems of three or more stars can reveal important clues about their formation and evolution. For instance, the coplanarity of angular momentum vectors between the outer and inner orbits in hierarchical systems can reflect the initial conditions during core collapse and fragmentation (e.g. Sterzik & Tokovinin 2002). Using traditional techniques of photometry and radial velocity studies, it has been shown that the angular momentum vectors are not correlated between the inner and outer orbits in systems with large period ratios, and therefore cannot be formed by traditional N-body dynamical simulations but instead require a process of rotationally driven cascade fragmentation (Tokovinin 2008). High precision astrometry achieved using LBOI presents a unique opportunity to study the orbital parameters, distribution of angular momentum, and coplanarity of orbits in hierarchical multiples (e.g. Hummel et al. 2003; Lane et al. 2007; Muterspaugh et al. 2008). Exceptional astrometric precision also makes it possible to search for small scale perturbations in binary orbits caused by faint non-stellar companions (e.g. Muterspaugh et al. 2006). Only eight systems with three or more components have been studied well enough to characterize each component's physical properties and the system geometry; many of the systems measured so far have non-coplanar orbits. Because stable systems of three or more stars are found in hierarchical configurations, with the inner pair having separations $<$ 10 times smaller than the outer pair, interferometric techniques that have a field of view several 100 times larger than its finest resolution, such as phase-referencing or baseline bootstrapping, are best suited to studying these multiple systems. Because our understanding of hierarchical star formation is still rudimentary, these types of studies will advance several areas in astrophysics in the coming decade.

8. Interacting Binaries

The evolution of close binary systems differs significantly from that of single stars. Mass-transfer between the two stars can alter the evolution, chemical composition, and orbits of both components. Aperture synthesis using LBOI provides a way to image the small spatial scales of interacting binaries in order to study tidal distortions, hot spot activity, and flow shapes. Current results include a direct diameter measurement of a star filling its Roche

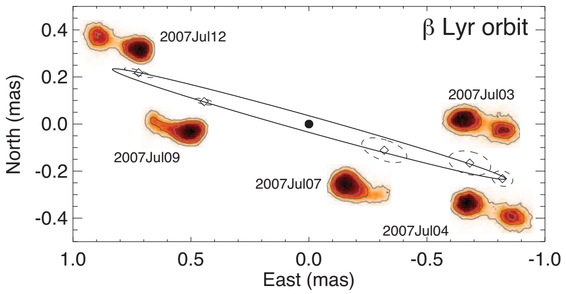

Figure 2: Visual orbit of the interacting/eclipsing binary β Lyr measured using the CHARA Array (from Zhao et al. 2007, Monnier et al. 2008). The small dashed ellipses indicate the errors in the position of the gainer relative to the donor at each epoch. Inlaid are reconstructed images of β Lyr (roughly 1.5 mas wide).

lobe in a semi-detached binary (Verhoelst et al. 2007) and the visual orbit of an interacting binary where reconstructed images and modeling show that the donor is elongated due to tidal distortions from Roche lobe filling and the gainer is embedded in a thick disk (Zhao et al. 2008; see Figure 2). Observations at such unprecedented resolutions have only recently become possible and will continue to prosper throughout the next decade.

9. Advances in Instrumentation and Access

The recent results in binary star astrometry described above, obtained with currently scheduled instrumentation, have scarcely tapped the current capabilities. Nevertheless, the technical capability is anything but static. Significant advances have been just recently fielded, are in active development, or in advanced planning.

Narrow-angle, differential astrometry, already demonstrated in prototypes to 20 microarcseconds, is currently in development and implementation at the Keck Observatory (Pott et al. 2008). Phase closure methods hold promise for detection of companions as faint as some of the brighter exoplanets (Zhao et al. 2008). New telescopes with larger apertures are coming on-line in arrays during the next few years: 1.4 m telescopes at the New Mexico MROI (Magdalena Ridge Observatory Interferometer, Creech-Eakman et al. 2008), and 1.4 and 1.8 m telescopes at the Flagstaff NPOI (Navy Prototype Optical Interferometer, DiVittorio et al. 2008). The GSU CHARA (Center for High Angular Resolution Astronomy) Array is beginning design of adaptive optics enhancement, promising up to several magnitudes in sensitivity gain (Ridgway et al. 2008). The Keck Observatory interferometric mode of the 10 m telescopes is adaptive optics supported, and Keck is implementing laser beacons for improved sky coverage (Wizinowich et al. 2006). The OHANA (Optical Hawaiian Array for Nanoradian Astronomy) project to link Mauna Kea telescopes with optical fiber will potentially open for interferometric use baselines as long as 800 m (Perrin 2006).

These developments will continue to enhance the science capability of our optical/IR arrays. Presently, access by the broad user community is limited, owing to insufficient operations support. The US Interferometry Consortium will prepare a proposal to the Decadal for a funding opportunity that, among its goals, would greatly extend open, competitive access.

Ground-based interferometry also provides a venue for the prototyping and demonstration of new techniques, and builds an expert community, prepared for future implementation of interferometric facilities in space. The SIM-Lite program has already demonstrated the technology for sub-microarcsecond single-measurement narrow-angle capability (Unwin et al. 2008). Further in the future, interferometry is the basis for numerous other mission concepts - e.g. Stellar Imager (Carpenter et al. 2006), and SPIRIT (Leisawitz et al. 2008).

10. Recommendations

Measuring high precision stellar masses of binary stars addresses a number fundamental astrophysical questions related to star formation, stellar evolution, and population synthesis. Resolving the orbits of binary stars and determining their masses across a large range of ages, metallicities, and evolutionary stages requires access to instrumentation that provides the highest possible spatial resolutions over the next decade.

References

Armstrong, J. T., et al. 2006, AJ, 131, 2643
Ballesteros-Paredes, J., et al. 2007, in PPV, 63
Baraffe, I., et al. 2002, A&A, 382, 563
Bender, C. F., & Simon, M. 2008, ApJ, 689, 416
Boden, A. F., et al. 2000, ApJ, 536, 880
Boden, A. F., et al. 2005, ApJ, 627, 464
Boden, A. F., et al. 2005, ApJ, 635, 442
Boden, A. F., et al. 2007, ApJ, 670, 1214
Bonnell, I. A., et al. 2007, in PPV, 149
Carney, B. W. & Latham, D. W. 1987, AJ, 92, 116
Carpenter, K. G., et al. 2006, SPIE, 6268, 63
Creech-Eakman, M. J. et al. 2008, SPIE 7013, 26
DiVittorio, M., et al. 2008, SPIE, 7013, 87
Goldberg, D., et al. 2002, AJ, 124, 1132
Gratton, R., et al. 2004, ARA&A, 42, 385
Gunn, J. E. & Griffin, R. F. 1979, AJ, 84, 752
Fekel, F. C. & Tomkin, J. 2004, Astron. Nachr., 325, 649
Heasley, et al. 2009, in prep.
Henry, T. J., et al. 1999, ApJ, 512, 864
Hillenbrand, L. A. & White, R. J. 2004, ApJ, 604, 741
Horch, E. P., et al. 2006, AJ, 132, 836
Hummel, C. A., et al. 2001, AJ, 121, 1623
Hummel, C.. A., et al. 2003, AJ, 125, 2630.
Lane, B. F., et al. 2007, ApJ, 669, 1209
Latham, D. W., et al. 1988, AJ, 96, 567
Latham, D. W., et al. 2002, 124, 1144
Leisawitz, D., et al. 2008, SPIE, 7010, 68
Loinard, L., et al. 2008, Rev. Mex. AA Ser. Conf., 34, 14
Kroupa, P. 2002, Science, 295, 82
Mason, B. D., et al. 20009, AJ, 137, 3358
Mathieu, R. R., et al. 2007, in PPV, 411
Mazeh, T., et al. 2002, ApJ, 564, 1007
Mazeh, T., et al. 2003, ApJ, 599, 1344
Monnier, J. D., et al. 2008, SPIE, 7013, 1
Muterspaugh, M. W., et al. 2006, ApJ, 653, 1469
Muterspaugh, M. W., et al. 2008, AJ, 135, 766
Perrin, G. 2006, Instrumentation, Mesure, Métrologie, 6, 1
Popper, D. M. 1980, ARA&A, 18, 115
Pott, J.-U., et al. 2008, arXiv:0811.2264
Prato, L., et al.. 2002, ApJ, 569, 863
Ridgway, S. T., et al. 2008, SPIE 7013, 102
Schaefer, G. H., et al. 2008, AJ, 135, 1659
Simon, M. 2001 in The Formation of Binary Stars (San Francisco: ASP), 454
Sterzik, M. F., & Tokovinin, A. A. 2002, A&A, 384, 1030
Tokovinin, A., 2008, MNRAS, 389, 925
Tomkin, J. & Fekel, F. C. 2006, AJ, 131, 2652
Torres, G., et al. 2002, AJ, 124, 1716
Unwin, S. C., et al. 2008, PASP 120, 38
Verhoelst, T., et al. 2007, A&A, 470, 21
Wizinowich, P. L., et al. 2006 PASP 118, 297
Zhao, M., et al. 2008, ApJ, 684, 95
Zhao, M., et al., SPIE, 2008, 7013, 45