Astro2020 Science White Paper

Binary and Multiple Star Systems at High Angular Resolution

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☒ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

Principal Author:
Name: Gail H. Schaefer
Institution: The CHARA Array of Georgia State University
Email: schaefer@chara-array.org
Phone: 1-626-500-0012

Co-authors:
Gaspard Duchêne (University of California, Berkeley)
Christopher D. Farrington (The CHARA Array of Georgia State University)
Tyler Gardner (University of Michigan)
Douglas R. Gies (Georgia State University)
Adam Kraus (University of Texas at Austin)
John D. Monnier (University of Michigan)
Lisa Prato (Lowell Observatory)
Stephen Ridgway (NOAO)
Rachael Roettenbacher (Yale University)
Robert E. Stencel (University of Denver)
Theo ten Brummelaar (The CHARA Array of Georgia State University)
Gerard van Belle (Lowell Observatory)

Abstract:
Binary and multiple star systems provide laboratories for measuring stellar masses and studying stellar evolution. The frequency of companions and properties within binary systems reveal imprints of their formation process and dynamical evolution over time. Observations of binaries at high angular resolution provide a way to measure high precision stellar masses to compare with theoretical models of stellar evolution, observe the alignment of orbital planes in hierarchical multiple systems, and study the exchange of mass and angular momentum during late evolutionary stages. This paper outlines several areas in the context of binary stars that can be advanced over the next decade.

Introduction

Stars often form in binary and multiple star systems (Raghavan et al., 2010; Duchêne & Kraus, 2013). Studying the frequency of binaries and the distribution of their orbital periods, eccentricities, masses, and mass ratios provide clues to understanding how binary stars form and evolve dynamically over time. In this paper we highlight several areas where the study of binary stars can be advanced over the next decade. The key questions that guide these investigations include: How do binaries form? What is the impact of multiplicity on disk lifetimes and planet formation? How do the external environment and binary properties within the system affect the evolution of binaries over their lifetimes? How is post-main sequence evolution shaped by binary populations?

Binary Frequency

The frequency of binary stars is dependent on stellar mass, with higher mass stars more likely to have a companion (Fig. 1; Duchêne & Kraus, 2013). The binary frequency also depends on environment (Fig. 1), with young associations having about twice as many binaries as the population of field stars (Duchêne & Kraus, 2013). Denser star forming clusters tend to have a lower binary frequency more consistent with the field, suggesting that binaries are dissolved through interactions in the cluster (Reipurth et al., 2007). Recent evidence indicates that the frequency of the closest binaries (< 60 AU) in the Orion Nebular Cluster is twice as high compared with the field, suggesting that only wider binaries are destroyed in these clusters; however, if most stars form in dense regions, this raises the question of why so many of these close binaries are missing from the field population (Duchêne et al., 2018). Traditionally, searches for binary companions have been conducted through radial velocity, photometric, and high angular resolution surveys using single aperture telescopes. The improved efficiency and precision of long baseline interferometry has opened the door to conducting high angular resolution searches at smaller angular scales (Sana et al., 2014; Gravity Collaboration et al., 2018). **A goal in the next decade is to obtain a complete census of stellar companions inside of 10 AU in nearby star forming regions.**

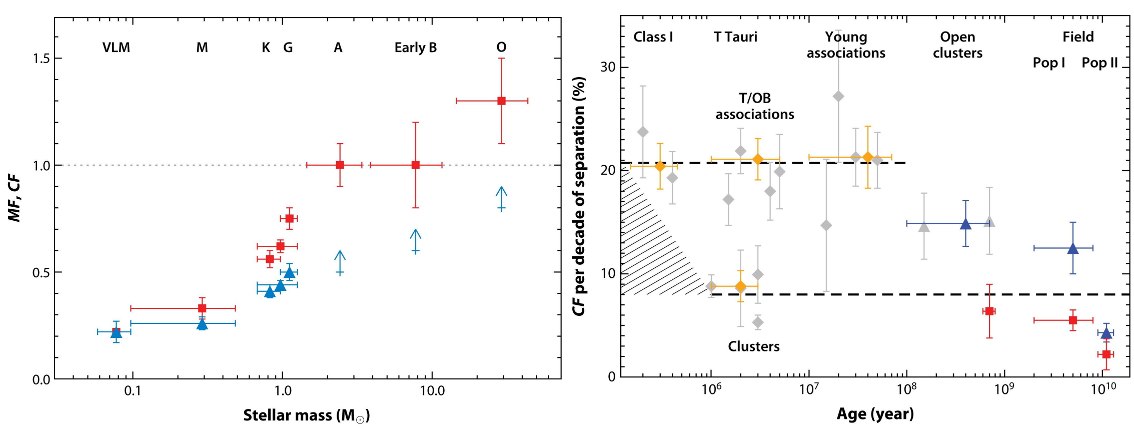

Figure 1: *Left:* Multiplicity and companion frequency versus stellar mass (Duchêne & Kraus, 2013). *Right:* Companion frequency versus age for field stars (solar-type stars in blue; low-mass star in red) and young star forming regions (orange). The results from individual surveys are marked in gray (Duchêne & Kraus, 2013).

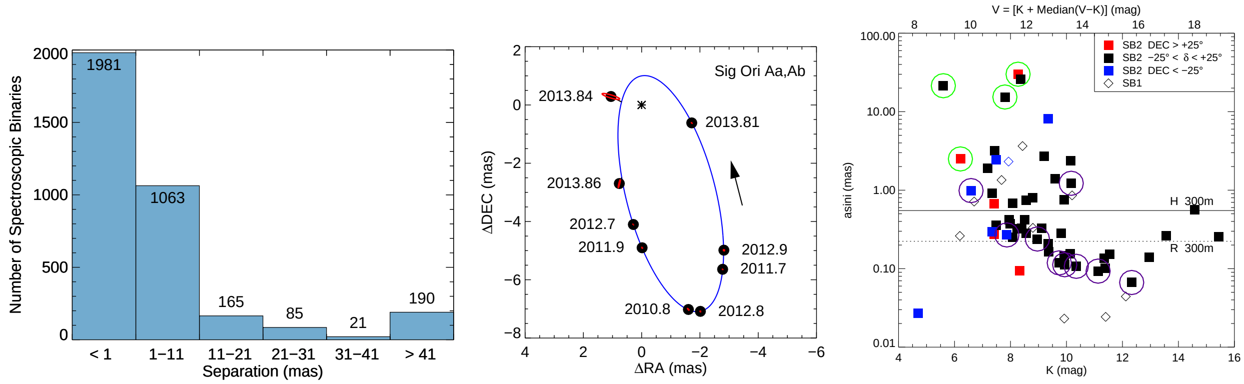

Figure 2: *Left:* Histogram showing the expected angular separation of known spectroscopic binaries. *Middle:* Visual orbit of the massive binary σ Orionis Aa,Ab (Schaefer et al., 2016). *Right:* Expected separation of known double (SB2, squares) and single-lined (SB1, diamonds) binaries in nearby star forming regions within 140−450 pc and spectral types ranging from F to M. The symbols are color-coded by their location on the sky. The solid and dotted lines show the angular resolution of a 300 m interferometer operating in the H and R-bands, respectively, The green circles indicate SB2 systems that have already been resolved (Boden et al., 2005; Torres et al., 2012; Simon et al., 2013; Le Bouquin et al., 2014) while the purple circles indicate eclipsing SB2s.

Precision Stellar Masses

Mapping the orbits of binary stars provides a critical tool for measuring dynamical masses of the component stars and testing theories of stellar evolution (Torres et al., 2010). Eclipsing double-lined spectroscopic binaries provide the largest number of stellar masses and radii, often measured with precisions of better than 1−3% (Torres et al., 2010; Feiden, 2015). Comparing the observed stellar properties (dynamical masses, radii, temperature, abundances) with those from evolutionary models provides critical tests of the assumptions made in evolutionary models, such as the assumed mixing length and amount of convective overshoot. The overall agreement is fairly good for solar-like stars. High-mass stars ($M > 10 M_\odot$) tend to be undermassive or overluminous compared with model predictions (e.g., Weidner & Vink, 2010; Massey et al., 2012). The models for low-mass stars ($M < 0.8 M_\odot$) systematically underpredict stellar radii by ∼5% and overpredict effective temperatures by 3−5% (Feiden & Chaboyer, 2012). This is a factor of two improvement over previous discrepancies of 5−15% (Ribas, 2006), accomplished by taking into account metallicity and age variations. The remaining discrepancies could be attributable to the efficiency of convection, stellar activity, and rotation in low-mass stars.

Spatially resolving the orbit of a spectroscopic binary provides another opportunity to measure the component masses and distance to the system. Figure 2 shows a histogram of the minimum angular separation of binaries in the 9th Catalog of Spectroscopic Binary Orbits (Pourbaix et al., 2004) based on their orbital parameters and parallaxes. Adaptive optics, speckle, and non-redundant aperture masking on large single telescopes can resolve systems down to 20−40 mas (e.g., Kraus et al., 2011; Schaefer et al., 2014; Horch et al., 2019). However, the majority of spectroscopic binaries have separations smaller than these limits. Long-baseline optical interferometry can resolve systems down to sub-milliarcsecond resolution and yield masses and distances with precisions of 1−3% (e.g. Schaefer et al., 2016; Gallenne et al., 2018; Lester et al., 2019, Fig. 2).

Star Formation and Pre-main Sequence Evolution

An increasing number of young stars with high precision dynamical masses and mass ratios (Torres et al., 2013; Stassun et al., 2014) has led to improvements in the theoretical models for pre-main sequence evolution (Paxton et al., 2011; Baraffe et al., 2015; Feiden, 2016). There is dramatic improvement in the agreement between models for masses between $0.5-1.4$ $M_{\odot}$ and ages $>$1 Myr, however, large discrepancies still exist for masses below 0.5 $M_{\odot}$ and ages $<$10 Myr (Simon & Toraskar, 2017). Differences among the models arise from the treatment of convection, opacities, electron screening in the interior, and abundances (e.g., Mathieu et al., 2007). At the distances to nearby star-forming regions ($\gtrsim 120-140$ pc), it becomes increasingly difficult to spatially resolve binaries discovered through spectroscopic surveys. As shown in Figure 2, long-baseline optical interferometry is critical to mapping the visual orbits of these systems.

The tidal influence of a close companion ($<$ 40 AU) can impact the lifetime of circumstellar disks, providing shortened timescales to form planets. Kraus et al. (2012) found that 2/3 of close binaries in the Taurus-Auriga star forming region had lost their disks within 1 Myr after formation, whereas $80-90\%$ of wide binaries and single stars retained their disks for at least $2-3$ Myr. Furthermore, a survey of *Kepler* planet-hosting stars revealed a deficit of binary companions at solar system scales (Kraus et al., 2016).

Orbital Alignment and Interactions in Multiple Systems

About 13% of stars are found in triple or multiple systems (Tokovinin, 2014). The alignment of the orbits between the inner and outer pairs in hierarchical systems can probe the initial conditions of star formation (Fekel, 1981; Sterzik & Tokovinin, 2002; Reipurth et al., 2014). For instance, orbital misalignments could be the result of turbulent fragmentation (Offner et al., 2010; Bate, 2012) or the dynamical decay of small-N clusters (Sterzik & Tokovinin, 2002), while co-aligned systems could be consistent with fragmentation of a planar disk. Measuring the relative alignment requires knowledge of both the inner and outer orbits, or at minimum, the relative direction of orbital motion. In a study of 20 triple systems by Fekel (1981), about 33% were found not to be coplanar, for the rest coplanarity remained a possibility. Based on a larger sample of 135 visual triple systems (of which only 22 have orbits measured for both pairs), Sterzik & Tokovinin (2002) found a mean relative alignment of $67-79°$, consistent with expectations from dynamical decay.

Long-baseline interferometry will increase the number of multiple systems where the relative orbital alignment can be measured. For example, the inner and outer pairs in the Algol and σ Orionis triple systems are not coplanar and orbit in opposing directions of motions (Zavala et al., 2010; Baron et al., 2012; Schaefer et al., 2016). A similar approach can be used to study the alignment of circumstellar and circumbinary disks measured from millimeter observations with the orbital planes in binary and multiple systems (Kellogg et al., 2017). In non-hierarchical configurations, tidal interactions from a tertiary component through the Kozai-Lidov mechanism can shrink the inner binary while ejecting the third component. This is a potential explanation for the formation of highly eccentric binaries and massive short-period binaries (Anosova, 1986; Reipurth et al., 2014). The recently discovered, highly eccentric binary HR 7345 ($e \sim 0.93$) could have formed this way; a search of the Gaia DR2 revealed a nearby X-ray and IR source with similar parallax and proper motion that could be the ejected component (Farrington et al., 2018).

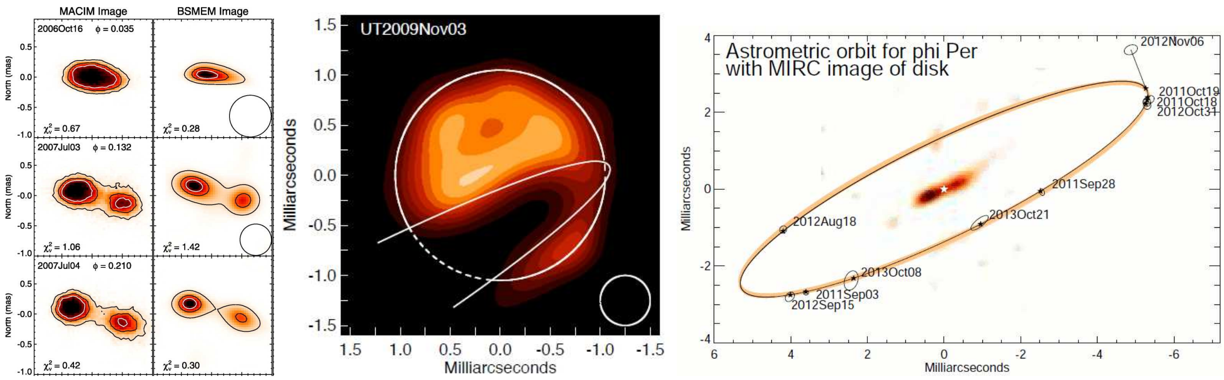

Figure 3: *Left:* Image reconstructions of the mass donor and accretion disk in β Lyr (Zhao et al., 2008). *Middle:* An image of the eclipse of ϵ Aur by its mysterious companion enshrouded in an opaque disk (Kloppenborg et al., 2010, 2015). *Right:* Image of the Be star ϕ Per spun up by past mass transfer with the astrometric orbit of its companion super-imposed (Mourard et al., 2015)

Mass and Angular Momentum Transfer in Interacting Binaries

Close binary stars are destined to interact as the initially more massive component grows to a radius comparable to the system separation. If the companion is not too small and escapes a merger, then the Roche lobe overflow (RLOF) from the mass donor to the mass gainer will lead to a reversal of the mass ratio. The binary β Lyr is an example of a system near the conclusion of RLOF, and observations from the CHARA Array (Fig. 3; Zhao et al., 2008; Mourard et al., 2018) show that the mass gainer is engulfed in a large accretion torus that hides the gainer from view. Mass accretion from the torus is expected to spin up the mass donor to the critical rate, inhibiting further mass accretion. The system may then experience substantial mass loss into a circumbinary disk that may obscure the entire binary from some orientations. The ϵ Aur system may represent a triple system in which a close pair and its dark circumbinary disk orbits the nearby F-supergiant (Lissauer et al., 1996). CHARA Array observations captured images of the transit of this dark disk across the face of the supergiant (Fig. 3; Kloppenborg et al., 2010, 2015). Following completion of RLOF, the former donor will appear as a stripped-down hot object, the He-burning core of the progenitor. These hot companions are usually lost in the glare of their now brighter mass gainer companions, but CHARA Array observations detected and mapped the orbit of the faint remnant of the ϕ Per system (Fig. 3; Mourard et al., 2015). High angular resolution observations provide us with the means to explore the advanced stages of binary evolution in unprecedented detail.

Novel Opportunities to Detect Companions

High Contrast Companions - Interferometry can resolve high contrast companions with magnitude differences down to $\sim$5 mag at milliarsecond separations (Gallenne et al., 2015). This is particularly useful for resolving the faint companions around evolved stars and has led to mapping the orbits of companions around pulsating Cepheids (Gallenne et al., 2018) and active RS CVn systems (Roettenbacher et al., 2015a,b). It can also resolve very low mass companions at small angular separations (Absil et al., 2011; Zhao et al., 2011; Marion et al., 2014).

Planets in Binary Systems - High precision astrometry of the component stars in a binary system provides a way to search for faint companions by their gravitational wobble. Early experiments at

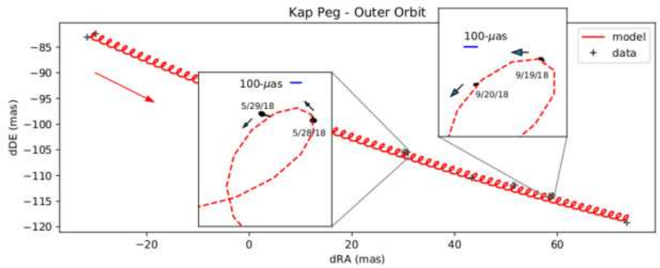

Figure 4: Astrometric precision using long-baseline interferometry (e.g. Gardner et al., 2018) to monitor the κ Peg binary system. The measurements confirm the earlier report (Muterspaugh et al., 2006) of a third star in the system through the wobble induced in the visual orbit of the main binary pair.

the Palomar Testbed Interferometer (Muterspaugh et al., 2010) proved promising. A new program at the CHARA Array is attempting to detect planets around A stars (Gardner et al., 2018) which are otherwise difficult to search using radial velocity methods due to the nearly featureless visible spectrum. Figure 4 shows recent data from this survey. While final absolute calibration is not available yet, the potential for 10 microarcsecond astrometric precision (Gaia-level or better) is there and deserves further exploration. This technique can be applied to hundreds of known binary systems with current sensitivity, but could become transformative with a dedicated facility.

Disk-eclipsed Binaries - Sky surveys continue to document an increasing number of transient celestial phenomena. An intriguing subset of objects are emerging that show variations in brightness interpreted as the transit of a circumstellar disk in front of a companion star in a binary system. The brightest member of this class is the F0 supergiant star plus disk binary, ϵ Aurigae, along with more than a dozen new candidates (including EE Cep, BM Ori and KH15D). Next generation interferometric imaging offers the potential to detect disk structures that are driven by dynamical forces, chemical transitions and thermal gradients. These include the effects of tidal spiral density waves, dust and planetesimal formation/evolution in disks, and orbital phase-dependent heating of the disk by the external companion star.

Recommendations for the Astro2020 Decadal

The study of binary populations and their fundamental properties requires several complementary approaches in the next decade. (1) Long-baseline interferometry to detect companions, map orbits, and image advanced evolutionary stages at the smallest angular separations. For a significant sample of binaries in nearby star forming regions, this requires reaching magnitudes of $K \sim 10$ mag and angular resolutions down to ~ 0.1 mas. Optimizing these opportunities could be achieved in cost effective ways by support for existing long baseline interferometers, and/or bold new proposals such as the Planet Formation Imager. (2) Imaging surveys at lower angular resolution, but greater sensitivity using 10 m to 30 m class telescopes to survey companions in more distant regions. (3) High resolution spectrographs with the potential of operating with adaptive optics to measure the radial velocity amplitudes, effective temperatures, and rotation properties of the component stars. (4) Photometric surveys (TESS, LSST, Zwicky Transient Facility, etc.) to discover eclipsing binaries in a broad range of environmental conditions. (5) Gaia will map the astrometric motion of the photocenter of close binaries, providing the inclination, and hence masses, for many double-lined spectroscopic binaries (Halbwachs et al., 2014, 2016). However, this approach has limitations, particularly for young stars where the variability of the components could affect the position of the photocenter, or for systems with periods extending beyond the mission lifetime. A combination of all these techniques will provide a census of binary stars and stellar masses across a broad sampling of environmental conditions and evolutionary stages.

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