Speckle Interferometry of Short-Period Binary Stars

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Abstract A research and development program for advancing speckle interferometry of short-period binary stars has seven major components. These are to: (1) create discovery target lists that are rich with potential binaries with under-observed components; (2) observe the binary targets with components with very small separations as guests at larger telescopes; (3) develop an atmospheric dispersion corrector to observe targets at high air masses from telescopes based in Hawaii; (4) continue the automation of speckle interferometry to survey thousands of binary candidates; (5) develop shaped-aperture masks to disperse the bright primary star light away from faint secondary star discovery zones; (6) refine the speckle data reduction procedures and develop bispectrum analysis to reduce multi-band differential photometric measurements; and (7) develop a simplified multi-frame blind deconvolution reduction technique for use with binary stars.

Introduction

Accurate determinations of stellar masses are critically needed to advance models of stellar evolution. Orbits determined by astrometric measurements of binary stars are the only assumption-free, model-independent way of directly measuring stellar masses. Binary orbits are established by observing the changing orientation of their two components, and then Kepler's Third Law is applied to yield dynamical masses.

The masses of stars in the middle of the main sequence are accurately known. This, however, is not the case for evolved stars, or for stars on either end of the Main Sequence. The masses of many of these types of stars are only known to 5%, while we need to achieve an accuracy of 1%. In the case of late-M stars, masses were recently found to be off by a factor of two, and these are the most numerous stars in the Universe! Few short-period binaries containing one of these stars as components are known because the brightness difference between the two components is large, making them difficult to observe.

The program described in this paper will employ automated speckle interferometry on telescopes equipped with masks developed by the exoplanet imaging community to discover many short-period, large differential magnitude visual binaries that have, as one of their components, a star of a spectral type or luminosity class with poorly known mass. This program's automation of speckle interferometry should make it feasible to observe the tens of thousands of double stars required to find a few hundred binaries with an under-observed component. Aperture masking-techniques should enable the discovery of heretofore invisible faint secondary components.

Automated differential photometric measurements should suggest spectral classifications, while multi-frame blind deconvolution reduction could improve precision. The program's target lists will be placed online so other observers can join the discovery process. Information on binaries discovered with under-observed components will also be placed online so observations can be initiated to establish their orbits and hence dynamical masses. Although well over 95% of the observations are not expected to discover the sought-after binaries, the astrometric and multi-band photometric information obtained should be of considerable value to the astronomical community.

Gaia, the Large Synoptic Survey Telescope, and other survey telescopes will suggest millions of close double stars that could benefit from observations made with systems employing the techniques developed by this program.

This program may lead to the development of four-meter class sparse aperture, speckle interferometry telescopes that should cost a full two-orders-of magnitude less than filled-aperture telescopes. Such automated telescopes would be highly productive binary-star-discovery and follow-up instruments.

Overall Program Objective

Improving our understanding of the basic evolution of isolated stars, *i.e.* stars that do not exchange mass, is a vital aspect of stellar research. The most influential parameter, by far, affecting single-star evolution is stellar mass. Advances in stellar evolutionary models are limited by the accuracy of known stellar mass (Malkov et al. 2012).

The objective of this program is to discover many short-period visual binaries that have, as one of their two components, a star of a spectral type or luminosity class with poorly known mass. Observations will be made using speckle interferometry because of its proven ability to economically observe binaries with separations below the seeing limit—usually the case for short-period binaries.

As will be detailed below, the closest binaries will be observed manually with student help as guest observers on larger telescopes, while the bulk of the observations will be automated. Borrowing technology from the exoplanet imaging community, masks will be used to preferentially diffract the light away from the bright primary star to provide a dark faint secondary star discovery zone. Automated, multi-band, differential speckle photometry will provide the estimates of spectral types needed to determine whether one of the components is of an under-observed type and hence worthy of follow-up observations. Finally, a very computationally-advanced reduction technique borrowed from the space surveillance community, multi-frame blind deconvolution, will be applied to the much simpler case of binary stars. This will allow reductions on fast PCs as opposed to supercomputers.

Measurements of binary stars are the primary, assumption-free, model-independent way of directly measuring (as opposed to inferring) stellar mass. As first suggested by Herschel in 1803, the two stars in a binary system act as mutual gravitational probes, and the first binary orbit was determined by Savary in 1830. For accurate single-star mass determinations, the two stars in the binary system cannot be too close, or mass exchange between the two components would affect their evolution. On the other hand, if they are too far apart, they will take hundreds or thousands of years to complete a significant portion of their orbit; a nearly complete orbit is a prerequisite for accurate mass determination. Thus short-period visual binary stars are well-suited for determining isolated-star stellar masses. Short periods, almost by definition, infer small separations—usually below the atmospheric seeing limit for ground-based telescopes. Thus special observational techniques are required, as discussed below in the Methods section.

The masses of stars in the middle of the Main Sequence are known with good accuracy from eclipsing binaries (Anderson 1991). Stellar types with the least well known mass are M stars, early stars (both white dwarfs and Main Sequence), and evolved giants and supergiants. The masses of Late M stars were recently shown by Trent Dupuy to be off by an amazing factor of two! (Dupuy et al. 2012; Dupuy et al. 2013). The program targets binary star systems with these types of under-observed stars.

How can the stellar masses of close visual binaries be directly determined? There are three complementary observational techniques:

(1) Light curves from the photometry of eclipsing binaries—also known as photometric binaries.

(2) Radial velocity curves via high resolution spectroscopy of binary pairs—i.e. spectroscopic binaries. Double-lined spectroscopic binaries also provide a parallax that is usually more accurate than trigonometric parallax (Farrington et al. 2014).

(3) Orbital determination via visual binary astrometry.

Typically it takes two of these techniques, working together, to obtain the individual stellar masses in a binary system (Mason et al. 1996). While all three techniques are vital and complementary, visual binary astrometry is our area of concentration.

How does visual binary astrometry lead to the determination of stellar masses? When viewed with the naked eye, close visual binaries appear as a single star. Viewed through a telescope at high magnification, they can appear as two separate or partially-blended stars. Repeated observations of the position angles and separations of a close binary over time can yield an apparent orbit—the programming of the binary's true orbit in three-dimensional space on the two-dimensional plane of the sky (Argyle 2012).

We know from Kepler's First Law that the orbits of two bodies trace out an ellipse. We also know from solid geometry that an ellipse tilted at any angle with respect to the line-of-sight is still an ellipse. Thus the apparent orbits of binary stars are ellipses. The measured position angles and separations of a binary can be fitted to an ellipse, providing an estimate of the apparent orbit.

Kepler's Second Law states that two objects in orbit around one another sweep out equal areas in equal periods of time. From all the possible orientations of an orbit with respect to the line-of-sight from Earth, Kepler's Second Law (given a sufficient number of observations) can be used to determine the specific orientation of a binary's orbit.

Kepler's Third Law states that for two bodies, the square of the rotational period is proportional to the cube of the semi-major axis of the true orbital ellipse. Newton extended Kepler's Third Law:

$$P^2 = a^3 / M_d$$

where P is the period in years, a is the semi-major axis in astronomical units, and M_d is the dynamical mass of the two stars in units of solar mass. The dynamical mass is simply the sum of the primary and secondary stellar masses, i.e., $M_d = M_p + M_s$.

It should be noted that the units of the semi-major axis in Newton's formulae are astronomical units, not arc seconds. Thus, we need to know the actual physical separation, not just the apparent angular separation. This is readily determined if we know the distance of the binary pair from Earth. Distances have been determined through the measurement of parallaxes—the displacement of nearby stars against distant stars as the Earth orbits the Sun. Parallaxes of over 100,000 stars were measured by the European Space Agency's telescope, Hipparcos (Perryman 2010). Gaia, launched by ESA in December of 2013, will, within a few years, provide many more highly accurate parallaxes (Eyer et al. 2013).

The overall research goal of this program is to improve our understanding of the evolution of stars by directly measuring, via visual binary astrometry, the dynamical masses of short-period binaries. Since the masses of stars in the middle of the Main Sequence are known with good accuracy, we will concentrate on binaries with a late M component, a very early component, or an evolved giant or supergiant component. As detailed below, there simply are not a sufficient number of these binaries with an under-observed star as a component to allow accurate determinations of stellar masses of these types of stars. Thus new binaries with these under-observed components need to be discovered. The overall objective of this program is to make the discoveries required to advance our knowledge of stellar evolution.

Specific Research Objective

Close binary astrometry concentrates on obtaining two values from true orbits: the orbital period in years, and the semi-major axis in arc seconds. These two values are derived from orbital solutions based on many measurements of the position angles and angular separations of binaries. The challenge is obtaining accurate position angles and separations over nearly complete orbits. When this can be done, and the parallaxes are known, the dynamical masses of binaries can be directly determined (Malkov et al. 2012).

Our program will concentrate on visual binaries with orbits between 100 days and 100 years. Binaries with periods less than 100 days typically have separations below the resolution limit of a 4-meter telescope. On the other hand, while observations of binaries with periods greater than 100 years are useful for other research objectives, the scope of the program requires that accurate, nearly complete orbits be obtained in a reasonable amount of time.

The *Sixth Catalog of Orbits of Visual Binary Stars* (Hartkopf et al. 2001) (VB6) includes published orbits of 795 binaries with periods less than 100 years but greater than 100 days. Of these, the binary with the widest angular separation is α Cen at 17.5″. Only 20 binaries have separations greater than 1.0 arc second. The remaining 775 pairs have separations of 0.03″ to 1.0″. This exemplifies the need for sub-arcsecond observations that will be made as part of this proposed effort.

Since the masses of stars in the middle of the Main Sequence are well known, we are concentrating on binaries with either early or late Main Sequence components or evolved components. If we define the "middle of the Main Sequence" (Class V dwarfs) as running from spectral classes A5 to K5, these comprise about 80% of the stars bright enough for our observing program. It is the other 20% at the two ends of the Main Sequence or those that have evolved off the Main Sequence for which observations are particularly valuable.

Of the 795 binaries within the limits noted above, only about two hundred pairs have a component of special interest, *i.e.* a component that is not in the middle of the Main Sequence. This number of stars is not nearly enough to accurately determine dynamical masses across this wide range of different stellar types. The specific research objective of our program is to discover many new short-period binaries with late M or very early Main Sequence stars, and evolved giants and supergiants as a component.

Method

There are four challenges that will work against the achievement of the program's primary objective. The first challenge is that short-period visual binaries have small separations—almost always below the seeing limit caused by atmospheric turbulence. Thus, an observational method that overcomes the limitations imposed by the seeing limit is required.

The second challenge is one of observational quantity. To discover new binaries with an under-observed component will require that we observe many thousands of double star candidates to find a few hundred short-period binaries with the needed components.

The third challenge is that, in most cases, the difference in magnitude between the primary (bright) and secondary (faint) components will be large. Typically, an M dwarf will be a very faint secondary, with a large differential magnitude difference between the two components, making the secondary difficult to detect. Much the same could be said for white dwarfs—also targets for the observational program. A similar large differential magnitude problem exists with evolved stars. Here the evolved, primary star in the binary is likely to be very bright compared to the lower-mass companion star.

The fourth challenge is to obtain differential photometric magnitudes in multiple color bands and then use these measurements to estimate the spectral types and luminosity classes of the two components.

Six basic methods are used to measure the position angles and separations of visual binaries. This list of methods is not exhaustive but covers the most common techniques:

(1) Visual micrometers have two illuminated crosshairs which are rotated to the binary's position angle; a micrometer screw then moves a crosshair to measure the separation (Couteau 1981).

(2) Images of visual binaries are obtained with a CCD camera. The position angles and separations can be determined with considerable accuracy, as long as the separations between the two components are significantly greater than the seeing limit (Tokovinin & Shatskii 1995).

(3) Lucky imaging overcomes seeing limitations by taking many hundreds or thousands of short exposures, each typically 10 to 30 milliseconds long, depending on the seeing (Law et al. 2006). Such short exposures "freeze out" the rapidly changing atmospheric effects. While most of the images are still badly distorted by "cells" of air of differing density passing over the telescope at high altitude and diverting the binary images in multiple directions, the air cells occasionally "line up" such that a

few "lucky" images are relatively undistorted. These lucky images can be automatically selected and stacked to produce images with a resolution that is only limited by the optical diffraction limit of the telescope. For a 0.2-meter telescope, the diffraction limit is about 1 arc second, while for a 2-meter telescope the limit is about 0.1 arc seconds (i.e. 100 milli arc seconds). Because a large number of frames have to be obtained, lucky imaging is not observationally efficient for simple objects such as binary stars.

(4) Speckle interferometry is similar to lucky imaging in that it also takes hundreds or thousands of short-exposure images. It differs from lucky imaging by utilizing all of the images. While the vast majority of the images are hopelessly scrambled in image space, the images are unscrambled in Fourier space to produce fringe patterns (Laberyrie 1970; McAlister 1985; Horch 2006). These patterns can then be converted to an "image" of sorts, called an autocorellogram, by taking the inverse Fourier transform. Alternatively, a real image can be obtained through bispectrum analysis, a computationally-intensive, four-dimensional technique using complex numbers to maintain the phase information of the observations via phase closure (Knox & Thompson 1973).

(5) Adaptive optics (AO) overcomes seeing limitations by sensing the phase distortion of the incoming light in real time (typically at a rate of several hundred Hz) and using this information to "warp" a small mirror in the optical train in a manner that will cancel out the atmospheric phase distortion. To sense the phase distortion, a high-power laser is often used to create an artificial star in the sodium layer of the atmosphere at about 40,000 feet elevation. The "Robo-AO" program has both automated and significantly reduced the cost of AO systems, although it still is about a million dollars (Baranec et al. 2014).

(6) Amplitude interferometry combines the light from two or more telescopes to produce interference fringes (ten Brummelaar et al. 2005). The baseline between the telescopes can be hundreds of meters, thus the resolution of these interferometers can be very high—just a few milli-arc seconds (McAlister, 1999). Binaries with very short orbital periods (months to days) can be observed. There are, however, very few of these expensive interferometers, and their ability to observe faint binary stars is limited.

Of these six methods, we have chosen speckle interferometry as the program's observational method. Due to the emphasis on short-period binaries, most of the observations must be of systems with separations below the seeing limit. Compared with lucky imaging, speckle interferometry utilizes all of the observations, providing higher signal-to-noise ratio solutions. While adaptive optics and amplitude interferometry each have their advantages, their complexity and cost place them well beyond the capabilities and scope of this program. The low cost of speckle interferometry—a robust technique which has been used for several decades of efficient observing of double and multiple stars—allows this method to be efficiently applied to discovering new binaries and following them after discovery.

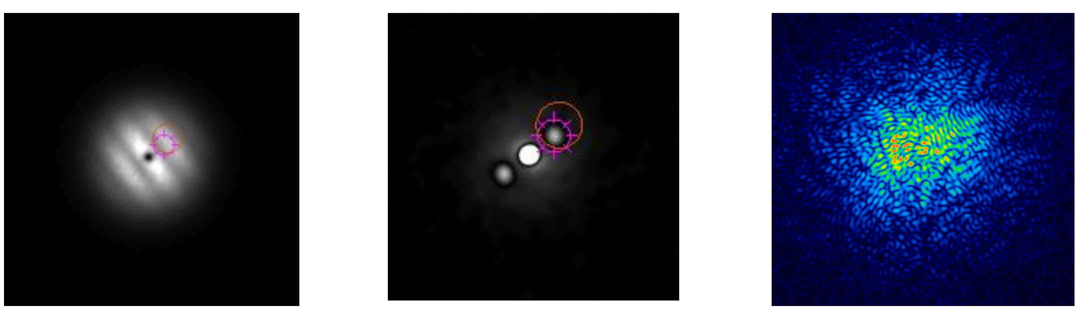

Figure 1. One of a thousand frames shows the speckles from a close binary. (Middle) The fringe pattern (from 1000 frames) in Fourier space of a binary with a separation of 0.22″ (left). The autocorellogram with the predicted position (brown circle) and measured solution (circle with spokes). Observations made with a student team on the 2.1-meter telescope at Kitt Peak National Observatory (right).

While speckle interferometry has, as described above, discovered a few hundred binaries with the requisite under-observed components, it hasn't discovered very many for two reasons: (1) a very large number of carefully selected targets have to be observed and there simply has not been the observational capability to do this, and (2) many of the desired components were secondaries simply too faint compared to the primaries to be detected without additional techniques such as specially shaped masks.

In addition to repeatedly measuring the position angles and separations of binaries over time, speckle interferometry can be used to obtain differential photometric magnitudes in multiple color bands. Not only is such photometry useful for theorists in the development of stellar evolutionary models, but it can be used to estimate spectral types, allowing us to determine whether or not the components of a binary star are under-observed and thus especially worthy of follow-up observations. However, reduction techniques such as bispectrum analysis are required to obtain accurate differential magnitudes (Baranec et al. 2014).

Short exposures suffer from a small amount of signal photons, and camera analog-to-digital converters operating at high speed are inherently noisy. However, the signal can be amplified within the camera itself prior to readout, reducing the read noise to an insignificant level. As the electron packets are being clocked out, a high voltage is applied between a cascade of output gain registers. Even at very high speeds, electron-multiplying (EMCCD) cameras have negligible readout noise.

This program's observational method of choice for discovering binaries with under-observed components will be speckle interferometry with EMCCD cameras. This method will allow us to circumvent the seeing limit, obtain the position angles and separations of close binaries, and also obtain differential magnitudes in multiple color bands.

Program Activities

While economical and robust, the observational method we have chosen, speckle interferometry with EMCCD cameras, is not without its challenges. To discover hundreds of binaries with under-observed components, determine their spectral types with multi-band differential photometry, and initiate observations to establish their orbits, it will be necessary to:

(1) Create discovery target lists that are rich with potential binaries with under-observed components.

(2) Observe the binary targets with components with very small separations as guests at larger telescopes. As few observatories are equipped for speckle interferometry, we will provide our own portable EMCCD-based speckle camera system, which we currently have.

(3) Develop and implement an Atmospheric Dispersion Corrector (ADC) to observe high airmass, far southern binaries from telescopes based in Hawaii.

(4) Automate speckle interferometry to survey thousands of binary candidates.

(5) Develop shaped-aperture masks to disperse the bright primary star light away from faint secondary star discovery zones. This large-differential-magnitude observing technology is borrowed from exoplanet imaging where the contrast ratios are typically five orders of magnitude more severe.

(6) Refine the speckle data reduction procedures and develop bispectrum analysis to reduce multi-band differential photometric measurements. Use these measurements to estimate the spectral types of the individual components.

(7) Develop a simplified multi-frame blind deconvolution reduction technique for use with binary stars.

Over the past two years we have created our first target lists, developed a portable EMCCD-based speckle camera and used it to make observations with students on several large telescopes, computerized an atmospheric dispersion corrector, and achieved initial automation of speckle interferometry on a small (0.25-meter) telescope. We have begun to develop shaped-aperture masks and bispectrum analysis. The seven program activities described below should, over the next few years, bring these efforts to fruition and produce a substantial body of data.

1. Create Discovery Target Lists Rich in Binaries with Under-Observed Components

This program requires that target lists of candidate objects be generated and maintained. As the overall intent of this program is to facilitate the discovery of new binary stars with under-observed components for the community, the program plan is not only to develop lists for our own use, but to publish these lists so they will be available to others in the astronomy community. This program will develop, publish, and maintain five lists contained in a database that is readily accessible to all, somewhat similar to the WDS "neglected doubles" list (see *adsabs.harvard.edu/abs/2001)*. The lists will be: (1) rapidly moving doubles, (2) unconfirmed Hipparcos pairs, (3) unconfirmed Tycho pairs, (4) Hipparcos "problem" stars, and (5) Gaia new discoveries and "problem" stars. These lists should be a valuable resource to the double-star research community.

Rapidly Moving Doubles

The first list will be comprised of double stars that have shown a rapid change in position angle (or separation) as reported in the *Fourth Catalog of Interferometric Measurements of Binary Stars* (INT4) (Hartkopf et al. 2001b), but to date do not have published orbits and are good candidates. Many of these rapidly-moving doubles are Hipparcos or Tycho discoveries that, since their discovery in 1991, have been observed only a few times—typically via speckle interferometry. A number of astronomers (Horch et al. 2012; Mason et al. 1999; Mason et al. 2000; Mason et al. 2001; Toknovinin et al. 2014) have been observing these potential binaries, but there are far more candidates than today's observers, using the currently available techniques, can handle.

Unconfirmed Hipparcos Pairs

Hipparcos discovered 3,383 potential doubles (Perryman et al. 1997). To date, 1,810 have not been confirmed, are in the magnitude range of 7-11, and have separations 0.1″ or wider (see Figure 2). Because these unconfirmed pairs are so close, it is expected that follow-up observations will confirm many of these as binaries, and some of these, in turn, will have under-observed components of special interest (i.e., stars not in the middle of the Main Sequence).

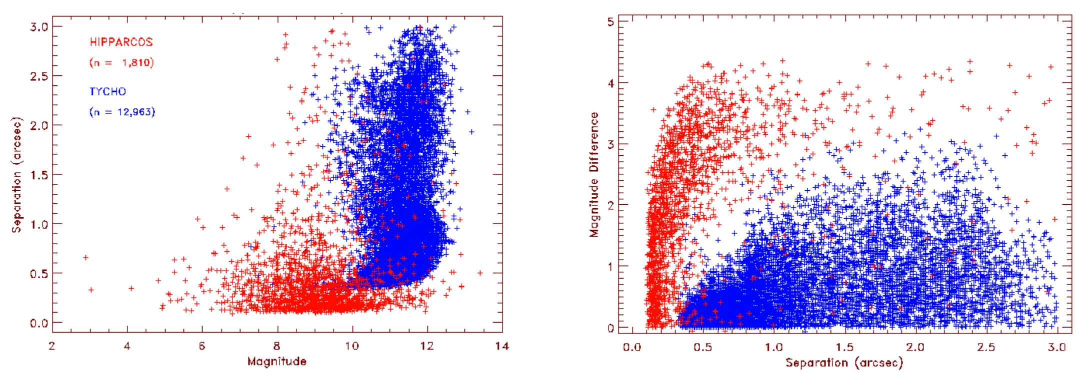

Figure 2. Unconfirmed Hipparcos and Tycho doubles: separation versus magnitude (left) and magnitude difference versus separation (right).

Unconfirmed Tycho Doubles

Another discovery source is the Tycho doubles (Høg et al. 2000). Tycho discovered 14,188 pairs. Approximately 91% of the Tycho doubles remain unconfirmed—no published follow-ups have yet been made. Of these, 2816 are targets with separations so small that only 4-meter class telescopes can handle them, 8701 are targets with separations that only 2-meter class telescopes (or 4-meter class telescopes) can handle, while 12,963 are potentially capable of being observed with 0.5-meter class telescopes (and larger telescopes).

Hipparcos Problem Stars

Another discovery source is the Hipparcos non-component (C) double star solutions, the so-called "problem" stars. There were 11,692 stars observed by Hipparcos which were unresolved but showed some indication of being double stars. Of these, only 754 have subsequently been resolved. The remaining 10,838 remain unconfirmed (no published observations since their 1991 anomalous solution). While some are not doubles, many will be doubles, and some of these doubles will be short-period binaries with an under-observed, non-middle-of-the-main-sequence component.

These Hipparcos problem stars fall into several classes. Two of these classes, G and O, are of special interest. G-code stars, of which there are 2,474, are apparently single stars that showed significant non-linear astrometric motion, *i.e.* acceleration or deceleration; thus there is an indication of orbital motion. If they were indeed binaries too close for Hipparcos to resolve, they could have opened up since 1991, or may be resolvable by telescopes with resolution limits beyond the 0.1″ limit of Hipparcos. The G-code systems are certainly of special interest—especially those with large parallaxes (*i.e.,* close to Earth). With our large differential-magnitude capability, it should be possible to resolve many of these G-Code doubles and, with follow up, some will turn out to be short-period binaries. The secondaries in large differential-magnitude binaries may often be faint because they are late-M stars, making such discoveries especially valuable.

O Code stars, of which there are 172, are orbital (astrometric) pairs that show photocentric motion. Thus their apparent angular semimajor axis is a photocentric orbit, and thus is just a minimum value. They are almost certainly binaries. There must be some magnitude difference between the two stars or they would not be photocentric, but not a large difference or the secondary would not have enough mass to cause a discernible photocentric motion (unless the faint component is a white dwarf or neutron star).

Unconfirmed Lunar and Asteroid Occultations

Lunar and asteroid occultations occur when the limb of the moon or asteroid temporarily blocks the flux from a distant star. The International Occultation Timing Association (IOTA) is a prominent volunteer organization which predicts occultations and organizes groups of members and others in the amateur astronomy community to observe these events. Quite frequently, occultation light curves generated show a step possibly indicating that the occulted star is a double (Herald et al. 2010; Loader et al. 2014). Most IOTA data is collected with video recorded at 25 to 30 frames per second. Since the lunar limb advances about half an arc second per second with respect to the background stars, the vector separations of components may be resolved with a precision of around 30 milli-arc seconds. If only one or two observations happen to record a step event and the step is only one or two frames in duration, there is a lack of confirmation that a double has in fact been detected, since scintillation is often pronounced at high frame rates. As a result, follow-up speckle observations could be crucial for ascertaining the true double state of a star, since an occultation of the star may not repeat for many years.

Gaia New Discoveries and Problem Stars

The Gaia advanced astrometric space telescope was launched in December 2013 by the European Space Agency (Perryman 2008). The first set of results is expected in late 2016. Gaia will uncover a bonanza of newly discovered binaries that will benefit from ground confirmation and follow up. Gaia will also generate a large number of "problem" stars with solutions similar to the Hipparcos G- and O-code solutions. These stars, a problem for Gaia, will be a windfall for this proposed effort. Follow-up observations should reveal many binaries with under-observed components. Since Gaia's resolution is about 0.5 arc seconds, many of their solutions may be resolvable via speckle interferometry with telescopes of only modest aperture.

2. Make Observing Runs as Guests at Larger Telescopes with a Portable Speckle Camera

We have developed and used a portable EMCCD-based speckle interferometry camera for our observations as guest observers (Genet 2013b), including three runs on the 0.5-meter telescope at Pinto Valley Observatory in the Mojave Desert Preserve (Genet et al. 2014a), runs during two winter seasons on the 0.5-meter telescope at Leeward Community College in Oahu, HI (Church et al. 2014), and two week-long runs on the 2.1-meter telescope at Kitt Peak National Observatory (Adam et al. 2014a; Adam et al. 2014b; Wallace 2014) (Figure 3).

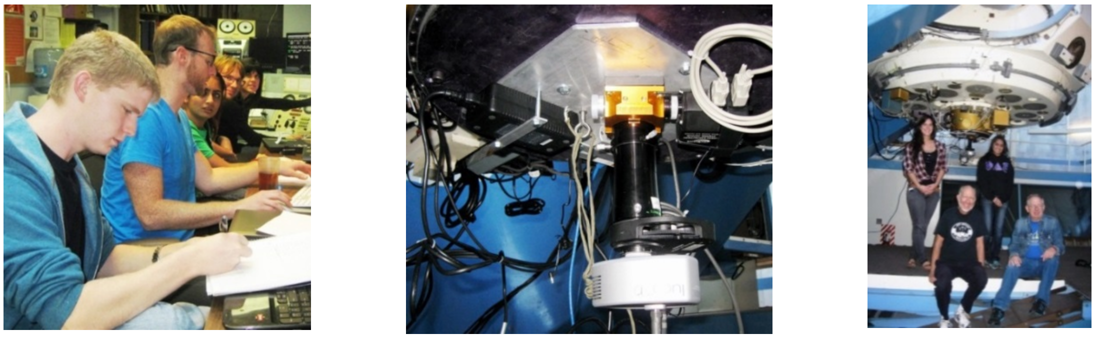

Figure 3. Five students (left) control the 2.1-m telescope at Kitt Peak National Observatory, operate our portable speckle interferometry camera, and keep up the log. The speckle camera (center) is the small silver-colored item directly under the Cassegrain focus (right), and is dwarfed by the telescope (Genet et al. 2014b).

We have concentrated our observations on refining the orbits of known, relatively short-period binaries, and obtaining additional data points on fast-changing doubles discovered by Hipparcos that could, potentially, be short-period binaries. This program will continue with students as guest observers at larger telescopes. Observing time on the 0.6- and 1.2-m telescopes at the Tierra Astronomical Institute (east of San Diego, CA), the 0.5-m telescope at the Pinto Valley Observatory (Mojave Desert, CA), and the 0.5-m telescope at Leeward Community College (Oahu, HI) have been confirmed. We are discussing observing possibilities with the Steward Observatory (1.5-m), and the Vatican Observatory (1.8-m).

3. Atmospheric Dispersion Corrector

Atmospheric dispersion only becomes an issue when observing through the high air masses relatively near the horizon. Atmospheric refraction affects wavelengths differently, acting like a prism. Blue light is bent more than red light. This skews the shape of an observed star. By using altitude data from a star catalog, a computer-controlled atmospheric dispersion corrector (ADC) can greatly mitigate the problem of atmospheric refraction by using a pair of counter-rotating Risley prisms. With an ADC, it will be possible to observe many southern binaries from Hawaii down to declinations of -50 degrees.

For his Master's thesis at California Polytechnic State University, Christiansen (2014) is developing a prototype atmospheric dispersion corrector (ADC) that uses two servo-controlled, counter-rotating Risley prisms for the correction. We plan to deploy a version of Christensen's ADC when working as guest observers on larger telescopes in Hawaii.

4. Automate Speckle Interferometry to Survey Thousands of Binary Candidates

Genet, in conjunction with Louis Boyd, developed some of the first practical automated telescopes. Their telescopes began operation in 1983, and have operated continuously since then at the Fairborn Observatory (founded in 1979 by Genet). The Fairborn Observatory was located for 10 years on Mt. Hopkins, and is now located near the Arizona/Mexico border (Boyd & Genet 1984; Hall & Genet 1988; Trueblood & Genet 1985; Genet 2011; see Figure 4).

Full automation of photometry revolutionized the study of variable stars, transforming the field from being data poor to data rich. Many automated observational programs were launched and successfully completed that would never have been attempted using manual observations. These included an automated search for exoplanet transits suggested by Borucki and Genet in 1992; the first successful transit detection with an automatic telescope was made by Henry et al. in 1999; and a simultaneous transit detection on another robotic telescope by Charbonneau et al. (2000). With full automation, a large increase in the quantity of observations can lead to major advances in the quality of scientific research (Genet & Boyd 1987). Full automation can also result in observations of higher precision and accuracy, given the ability to efficiently conduct observations for calibration and quality control (Young et al. 1991; Henry 1999).


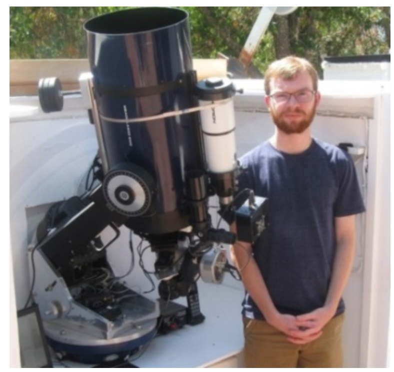

Figure 4. Seven automatic telescopes are on the left at the Fairborn Observatory's robotic observatory on Mt. Hopkins in 1989 (left). A quarter century later, Alex Teiche, an undergraduate student at California Polytechnic State University, stands beside the 0.25-meter telescope at the Orion Observatory (right) on the morning after the first speckle automation was achieved in September 2014.

Automation of astronomical observations provides a number of benefits over manual observations, as pointed out by Boyd and Genet (Boyd et al. 1986). These include lower staffing costs because observers are not required, lower maintenance costs because the systems are designed to operate with minimal intervention, observations which are repeatable and can be standardized, and telescopes which can be sited in locations that are difficult, uncomfortable, or expensive for human observers.

Speckle automation was recently achieved by Teiche as part of our feasibility demonstration program (Teiche et al. 2014). Our first automated telescope has an aperture of 0.25 meters, so it can only observe binaries with a separation down to 1 arc second (Figure 4). This small telescope will initially be dedicated primarily to the task of refining hardware, software, and procedures for the automation of speckle interferometry. Peter Heatwole, for his EE Master's thesis at California Polytechnic State University, plans to extend Teiche's pioneering work.

One component of this proposed program will extend automation to a larger, 0.45 meter aperture telescope. The optics, optical tube assembly, and control system will be provided by the Orion Observatory, while the mount will be manufactured by Equatorial Platforms. With this telescope it will be possible to observe binaries with a separation of 0.5 arc seconds. An Andor iXon, back-illuminated EMCCD camera on long-term loan from Gravic Lab will be the principal detector for this automated system. This camera has a peak quantum efficiency of over 90% and is unusually sensitive at longer wavelengths, which will be helpful when observing binaries with late-M components.

Full automation will allow us to undertake the extensive, large-scale discovery programs needed to discover many binaries with under-observed components. The weather at the Orion Observatory is excellent. We can observe about 200 nights a year for an average of about 8 hours per night, and can obtain 15 or more speckle observations per hour per telescope.

This provides roughly 24,000 speckle observations per telescope per year. With this volume of observations, not only can a large-scale discovery program be undertaken, but many calibration and quality-check observations can be included.

For many close double stars, only the color magnitudes of the combined pair are known. Obtaining automated differential magnitude measurements in several color bands is required to determine the spectral types of the components in double star systems. Knowing the component spectral types informs us whether either component is of interest to this effort. Quite precise differential photometry (albeit not automated) has been obtained in two color bands on many stars (Horch et al. 2004).

To discover the hundreds of binaries being sought, many thousands will be observed. Rather than discarding the "rejects," they will be placed online for the benefit of the double-star community.

5. Develop Masks to Create Dark Discovery Zones for Faint Secondaries

As mentioned previously, binaries with under-observed components will usually have large differential magnitudes. The light from the bright primary swamps the light from the faint secondary. Our masks are based on work at Princeton University where they are being developed for imaging exoplanets with space telescopes.

Shaped aperture masks diffract the bright light from the primary star away from "discovery zones," allowing faint secondaries to be discovered. Many shaped masks have limited-angle discovery regions, so one must rotate these masks to fully survey the neighborhood of a star (Kasdin et al. 2003). Other mask species provide full 360-degree visibility around a star, but do so at the expense of throughput or resolving power (Vanderbei et al. 2003). In general, larger discovery zones are associated with poorer contrast.

Other mask varieties have been proposed in the context of high-contrast imaging, including Lyot coronography and apodized masks. Lyot coronagraphs use a series of lenses and masks to isolate and remove centrally-incident light from the image (Sivaramakrishnan et al. 2001). These systems require accurate manufacturing techniques and precise positioning to function properly (Singh et al. 2013). Apodized masks, also called gradated masks, are used much like shaped aperture masks but feature a continuous transmission profile rather than only complete transparency or complete opaqueness. The smooth patterns theoretically can provide results superior to shaped aperture masks, but these results are difficult and expensive to achieve in practice. Single full-aperture shaped masks are expected to provide sufficient contrast to meet the initial goals of our program. However, we expect, in the future, to develop Lyot mask systems, as it seems likely that they will further extend our ability to detect faint, close secondary stars.

Foley, Zimmerman, and Rowe are simulating the potential effectiveness of various aperture mask designs using Rowe's speckle interferometry simulator (Foley et al. 2015). The simulator takes into account atmospheric distortion and camera noise, producing a result that is more realistic than an idealized diffraction pattern. The prolate-spheroidal mask (Figure 5) will be tested alongside "spider web" masks produced by Zimmerman specifically for this program. Masks with promising simulation results are being manufactured using CNC tools and tested with manual rotation on a telescope at the Orion Observatory. The most promising masks will then be incorporated in automated speckle interferometry telescopes at the Orion Observatory as part of Foley's Master's thesis research (Foley 2014).

While a single, full-aperture, shaped pupil mask looks promising, additional masks of various sorts can be placed at the image plane or Lyot stop. Adding such masks increases the degrees-of-freedom in the design space, which should allow a larger contrast ratio to be reached and therefore difference in magnitude. Although these additional masks would be much smaller, with tighter manufacturing and alignment tolerances, the contrast-ratios sufficient for double star research (approximately 10^2 to 10^3) are more modest than those for exoplanet imaging and so may be within reach.

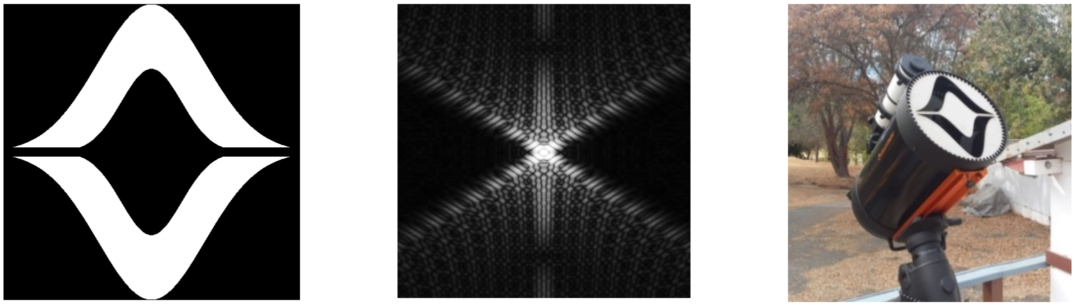

Figure 5. Foley's mask (left) is based on the Spergel–Kasdin prolate-spheroidal mask originally described by Kasdin et al. (2003). It produces the diffraction pattern (middle) plotted on a nonlinear brightness scale. Note the two triangular secondary star "discovery zones" that are relatively free of diffracted light from the primary star. A CNC cut mask (right) is shown on a C-11 Telescope.

There are a number of young giant planets (such as the HR 8799 system, to give the most famous example) that are within reach of 10^5 contrast, and have been imaged from the ground with AO systems at Keck, Palomar, and GPI. A contrast ratio of 10^8 is the design figure being used for space-based science goals.

6. Data Reduction, Bispectrum Analysis, and Spectral Classification

A number of speckle interferometry reduction programs have been written by individual astronomers to reduce data. While these programs work well, they were not intended for widespread use, so they are not extensively documented or "user friendly." Rowe developed software called PlateSolve 3 (PS3) as a general purpose program for stellar astrometry. Given an image with a sufficient number of stars—but without any information as to plate scale, camera angle, RA, or Dec— PS3 quickly determines these parameters [US patent 8,401,307]. Besides this plate-solving capability, PS3 also has many other capabilities such as image calibration, aligning and combining images, etc.

A speckle interferometry reduction capability has been added by Rowe to PS3 (Rowe & Genet 2014). A preprocessing capability calculates and averages the power spectra of all the frames in the FITS data cubes, allowing this time-consuming process to be completed prior to analysis. The program can apply both high- and low-pass Gaussian filters to the data. The science frames can be processed alone or deconvolved with data obtained from a single star located near the double.

PS3 speckle interferometry reduction can be run in one of two modes. In the "manual" mode, individual double-star FITS cubes are selected from a data base, one at a time. Matching deconvolution single-star FITS cubes can also be selected if desired. In the semi-automatic mode, the FITS cubes for both the double star and single deconvolution star are loaded automatically, along with any *a priori* estimates of the position angle and separation of the double—typically the last observation published in the *WDS*. With these inputs, PS3 uses an algorithm to obtain an automatic solution and displays the resulting autocorellogram. The user can accept this solution with a click, or override the automatic solution and provide a manual solution. In either case, both the results and the autocorellogram image are automatically recorded. In the semi-automatic mode, a user can process hundreds of double stars an hour.

An important development, with respect to the high volume of reductions required for use with fully automated telescopes, is a more completely automated reduction process. The automated reduction process will be refined to reduce the number of mistaken solutions it makes (ones that are often patently obvious to a human), and to also develop a metric for the certainty of the automated solutions. If the automated error rates for high certainty solutions can be brought to very low values, then we may be able to avoid human intervention for the vast majority of the observations. However, it is expected that some human intervention may always be required for low certainty automated solutions; otherwise these observations would have to be discarded.

Rowe is working on a speckle imaging addition to PS3, namely bispectrum analysis, also known as triple correlation (Knox & Thompson 1974; Lohmann et al. 1983; Weigelt 1977). Unlike speckle interferometry power spectrum averaging which we have been using, speckle imaging recovers the object phase information via phase closure. Image reconstruction, such as bispectrum analysis, is required to accurately determine differential photometric magnitudes. These magnitudes will be used to estimate spectral types and luminosity classes. A technique such as isochrone matching may also be used to make these estimates (Davison et al. 2009). This technique can also be used to estimate individual stellar masses and, in some cases, ages.

7. Multi-Frame Blind Deconvolution Reduction

Much progress has been made in speckle imaging over the last two decades. Iterative techniques have been developed to reconstruct images from the sequence of short-exposure images. The general name for these algorithms is multi-frame blind deconvolution (MFBD). MFBD is a computer-intensive image reconstruction technique that iteratively utilizes the full set of frames to converge on the best estimate of the set of point spread functions (PSF) and the image of the object (Hirsh et al. 2011).

Although MFBD techniques have been developed and applied to reconstructing images of extended objects such as satellites in orbit around the Earth (space surveillance), they have not been widely applied to the problem of reconstructing binary stars.

A good initial estimate of the PSF can speed up convergence. Similarly, an accurate model of the object can increase the effectiveness and accuracy of the reconstruction. In the case of binary star astrometry, the image can be described very simply by three parameters: position angle, separation, and differential magnitude of two point objects.

The proposed program will develop an MFBD algorithm which will be specifically designed for the reduction of binary star speckle interferometry. For our simple binary or multiple star case, it could be both fast and make optimal use of the information in all the frames in an iterative manner, producing information of both higher accuracy and precision than can be produced by other techniques.

Conclusion

The most influential parameter affecting single-star evolution is stellar mass. The accuracy of evolutionary models is limited by the accuracy of known stellar mass. Binary star orbits are the only way of directly measuring (as opposed to inferring) stellar mass. By discovering and initiating astrometric observations of short-period binaries with evolved components or components on either end of the Main Sequence, this program should significantly increase the accuracy and size of the database of known stellar masses where it is most needed. Any time a new level of accuracy is achieved for a key parameter vital to understanding, such as stellar mass, a transformation of knowledge is possible.

Automation of speckle interferometry should allow the proposed massive observational program to be undertaken at exceptionally low cost. As has been the case in astronomy and elsewhere, an order-of-magnitude increase in the quantity of observations brought about by automation can result in unexpected breakthroughs. Shaped-aperture masks should allow close binary stars with a large differential magnitude difference between the components to be observed. By iteratively using the full set of observations to converge on a solution, multi-frame blind deconvolution (MFBD) reduction more fully utilizes observations to determine binary parameters. Together, these three technologies should produce a potent discovery system with the potential to significantly advance and transform our knowledge of stellar evolution. Taken together, automation, shaped aperture masks, and multi-frame blind deconvolution have the potential of significantly advancing the field of visual binary astrometry for many observers.

In order to find a few hundred binaries with an under-observed component, tens of thousands of double stars will have to be observed. Reporting these observations will, in its own right, be a major contribution to double star astrometry.

Although their spatial resolution is limited, when Gaia, LSST, and other survey telescopes come online, they will suggest thousands, perhaps even millions of close double stars that could benefit from this program's high resolution, large differential magnitude observational capabilities (Terziev et al. 2013). This program will help prepare for the coming flood of targets. Observations with our systems and other similar systems could transform our knowledge of binary and multiple stars in many areas.

We will rely, as we have in the past, on students from a number of different institutions and our well-developed community of supporting astronomers, engineers, and technical experts. Frequent conferences, workshops, and extensive communications will help to keep our diverse binary star research and development community on course (Genet 2013b; van Belle & Genet 2014).

Our student-centered research and development program draws on community college students (some of them first-year college students also finishing up high school), undergraduate university students, and Master's students (Genet et al. 2010). It benefits students by enhancing their educational careers with early, hands-on experiences in research and development. This often results in entry into choice graduate schools with a scholarship and a successful career in science or engineering. As pointed out in the decadal recommendations to the National Academy of Sciences (Henry et al. 2009), "The most important recommendation is to provide the educational foundation required so that a new generation of astrometrists can make best use of the rich data sets that will arrive in the coming decade."

This program naturally brings together the binary-star-astrometry, exoplanet-imaging, and space-surveillance communities in a synergistic manner. Although we are borrowing shaped-aperture mask technology from exoplanet imaging, and multi-frame blind deconvolution from space surveillance, reverse innovation could occur if our modestly-funded program came up with innovations that significantly impact these more generously funded areas. This is sometimes referred to as "trickle-up innovation" (Govindrajan & Trimble 2012).

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