Binaries with A-type primaries - A comparison between dynamical masses and theoretical models

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Introduction

With high angular resolution adaptive optics imaging, we have obtained observations of 26 binary systems with projected separations $<$100 AU. These images form part of our ongoing Volume-limited A-Star (VAST) adaptive optics survey. Half of the stars in the sample have sufficient historical measurements to allow for refinement of their orbital elements, and half of the sample will be monitored for future orbit fits. For each system with an estimated orbit, the dynamical system mass obtained was compared with the system mass estimated from mass-magnitude relations. Discrepancies between the dynamical and theoretical system mass can be explained by the presence of a previously unresolved spectroscopic component, or by a non-solar metallicity of the system. Using this approach to infer the presence of additional companions, a lower limit to the fraction of binaries, triples, and quadruples can be estimated as 39, 46, and 15 per cent, for systems with at least one companion within 100 AU. The fraction of multiple systems with three or more components shows a relative increase compared to fraction for Solar-type primaries resolved in previous volume-limited surveys. These proceedings are based on our recently accepted manuscript, which is available at `http://arxiv.org/abs/1112.3666`. The definitive version will be available at `www.blackwell-synergy.com`.

1. Sample and observations

The total sample includes 26 systems with projected separations less than 100 AU and is drawn from the ongoing VAST survey [1, 2], an adaptive optics (AO) imaging survey of A-stars within 75 parsecs. Of the 26 systems, 13 have a substantial number of previous measurements, and these systems comprise the orbit subsample. For the remaining 13 systems, there is insufficient coverage to fit an orbit, with 11 newly resolved, and these binaries comprise the monitoring subsample. Figure 1 plots the measured magnitude difference as a function of separation for the orbit monitoring sample. The distribution of the sample on the color magnitude diagram (CMD) is plotted in Figure 1. Given the rapid evolution of massive stars off the Main Sequence, the position of an A-star on the CMD provides a method to estimate of the age of the system based on a comparison with theoretical isochrones. The inferred age of the system from the CMD is combined with the dynamical system mass from the orbit and system photometry from the literature to test mass-magnitude relations at the corresponding age.

Near-infrared images were obtained on all targets with AO systems operating on telescopes ranging in

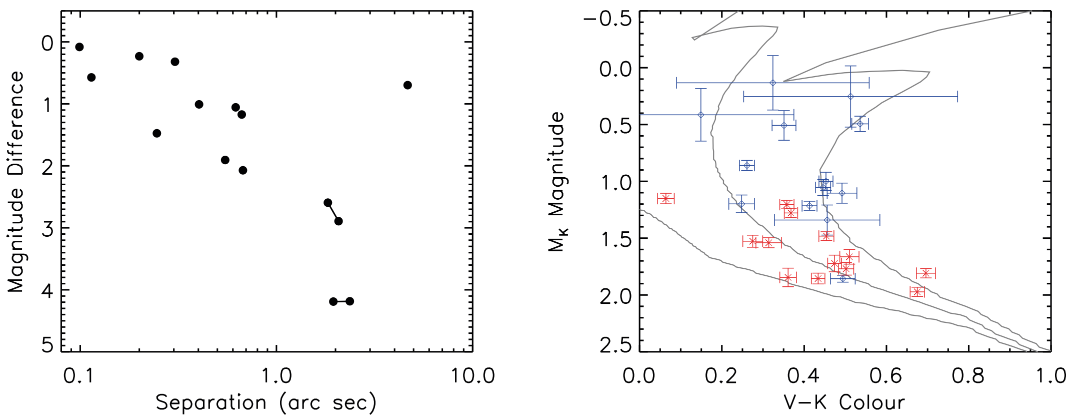

Figure 1: *(left panel)*: The magnitude difference between primary and secondary for each binary system within this study with an orbit determination. *(right panel)*: A colour-magnitude diagram of the 26 stars discussed within this work, plotted alongside three theoretical isochrones. The blue symbols represent systems for which an orbit has been estimated within this study, and the red symbols represent systems for which further measurements are required prior to an orbit determination. The three isochrones are at ages of 100, 500, and 800 Myrs [3].

diameter from the 3m Shane to the 8m Gemini and VLT. For most observations, the filter was a narrow or broadband filter within the *K* bandpass, though some images were taken within the *J* and *H* bandpasses. Both the primary and secondary of the pairs were unsaturated in the AO images, simplifying the astrometry and photometry measurements. A subset of the observations were obtained from the CFHT and ESO Science Archive Facilities. The AO science images obtained were processed with standard image reduction steps including dark subtraction, flat fielding, interpolation over bad pixels and sky subtraction. To align all the images, the centroid of the bright primary was obtained in each exposure by fitting a Gaussian to the core of the central point spread function. For each system resolved within the observations, an empirical PSF was determined from the radial profile of the primary, after masking any close companion. The empirical PSF was then fit to the position and intensity of both components of the system, providing a measure of the separation, position angle, and magnitude difference. Uncertainties within the photometry and astrometry were estimated from the standard deviation of the photometric and astrometric measurements from each individual exposure before combination.

2. Orbit determination

For the 13 binaries in the orbit monitoring sample, the new data were combined with previous measurements contained within the Washington Double Star (WDS; [4]) Catalog and a fit was performed for the orbital elements and an estimate of the dynamical mass was determined. These archive measurements were obtained using a variety of observational techniques, and date back to the 18th Century, however, only data with formal errors reported for each individual measurement of separation and position angle were included within the fitting procedure. As in some cases the statistical uncertainties were not provided in the WDS Catalog, we searched the literature for them. A detailed listing of the individual measurements used for the orbital determination will be made available at the Strasbourg astronomical Data Center (CDS - `http://cds.u-strasbg.fr`) as part of the complete description of this project [2]. Our orbit fitting approach utilises the method presented by [5], and demonstrated by an application to measurements of the T Tau S system [6]. This method is similar to the grid-based search technique developed by Hartkopf et al., 1989 [7]. Examples of two orbit fits are shown in Figure 2.

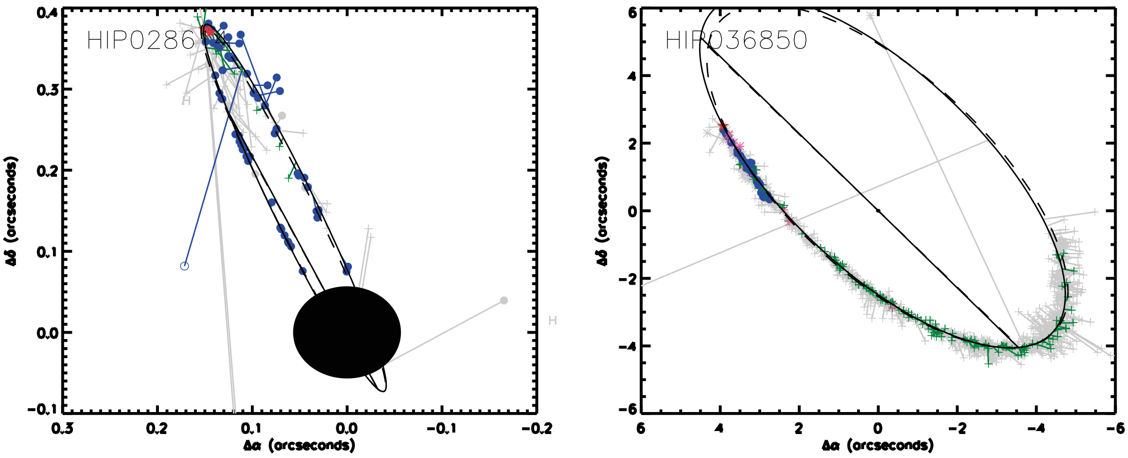

Figure 2: Combining our high resolution observations with historical measurements, refined orbits for 2 binary systems are plotted (HIP 28614, HIP 36850). The previous orbital fit, obtained from the Sixth Orbit Catalog, is plotted for reference with a dashed line. Each plot uses a similar symbol scheme to the Sixth Orbit Catalog. Our high resolution observations presented within this study are plotted as filled red stars. Symbols in grey represent those measurements presented without formal errors, and are not used while estimating the orbital parameters. The 57mas radius black disc represents the resolution limit for K-band observations at an 8-metre telescope.

3. Comparison of dynamical and theoretical masses

3.1 *Theoretical mass-magnitude relations*

The dynamical system masses estimated from the fitted orbital parameters were compared with four different grids of evolutionary models. The theoretical grids [3, 8, 9] covers a significant portion of the lifespan of a typical A-type star including post-Main Sequence stages, so we applied a maximum age cut-off at 1 Gyr for these targets that have not evolved off the Main Sequence. In addition to these grids, models from [10] were obtained in order to study a pair of lower-mass companions resolved around HIP 44127. Each grid was converted into the photometric systems used within this study - Tycho V and 2MASS K_S [11], before producing a high resolution ($dM/M_\odot = 0.001$) mass-magnitude relation, created through cubic interpolation of the grid data. The absolute V- and K-band magnitudes were calculated from the V-band magnitude differences obtained from the literature, and the K-band magnitude differences measured within this study. Within the A-type star mass range, the mass-magnitude relations significantly change as a function of the age of the system due to the rapid evolution of A-type stars across the CMD. The age of each system is therefore estimated, based on the position of the primary on the CMD, before a mass for each component is estimated from the mass-magnitude relations. The masses of each component are summed to produce an estimate of the total system mass, designated the theoretical system mass.

3.2 *Known/Suspected higher order systems*

Systems with significantly higher dynamical masses than theoretical system masses obtained from mass-magnitude relations are strong candidates for multiple systems with unresolved components which have not been detected in the current AO images or in spectroscopic observations. These systems are indicated in Figure 3, and a number are known to have spectroscopic companions. Two systems with the signature of a possible unresolved component, but no known SB orbit are HIP 17954 and HIP 93506. Sensitive spectroscopic observations of both systems may lead to the detection of the spectral lines from an unresolved lower-mass component. A similar phenomena is observed for the HIP 47479 system, although the

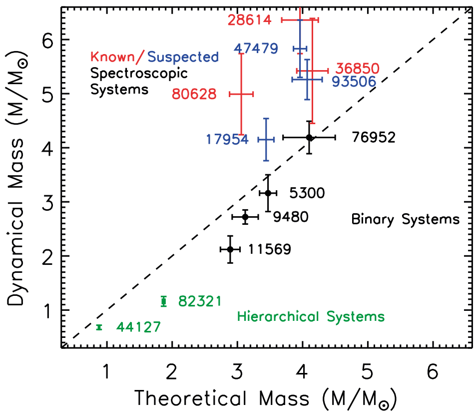

Figure 3: A comparison can be made between the dynamical mass determined from the orbit and the mass estimated from theoretical mass-magnitude relations for the stars within the orbit subsample (the Marigo et al. (2008) models are used for this example [8]). The systems with an A-type star primary which are known to consist only of two components are denoted as black points. Two hierarchical systems were fully resolved with our data, and the lower-mass pair of each system are in green. The systems which have a significantly discrepant dynamical mass can be explained by the presence of an unresolved spectroscopic companion within our data. The targets with known spectroscopic components are plotted in red, while those systems with evidence suggesting a previously unknown spectroscopic component are plotted in blue.

low number of measurements used to determine the orbit is particularly low, making the dynamical mass less certain. The narrow spectral lines of HIP 47479, implied by the low measured stellar rotational velocity [12], make it an ideal candidate for spectroscopic follow up. Previous spectroscopic observations of this system reveal $v \sin i$ variations with a magnitude of 40 km s^{-1} [13].

From the orbit monitoring sample of 13 systems, and only considering stellar companions within 100 AU, a lower-limit on the higher-order multiplicity of A-type stars can be estimated by using the mass discrepancies to identify additional components. Assuming the suspected unresolved companions described earlier in this section are higher order systems rather than binaries, there are five double, six triple, and two quadruple systems within the orbit subsample, corresponding to frequencies of 39%, 46%, and 15%, respectively. This lower-limit shows an enhancement on the higher-order multiplicity of A-type stars when compared with Solar-type primaries (74% double, 20% triple, and 6% quadruple or higher-order - [14]), and is more consistent with the fraction reported for more massive O-type primaries (46% double, and 54% triple or higher-order - [15]).

3.3 *Binary systems*

As show in Figure 3, the four systems HIP 11569, HIP 9480, HIP 5300, and HIP 76952 have dynamical masses similar to the theoretical system masses, and these systems represented tests for which the dynamical masses were compared to masses derived from theoretical models. Due to their rapid evolution across the CMD compared to lower-mass solar-type stars, binaries with A-type components are ideal targets with which to test theoretical models, since the ages can be estimated. Of the four binary systems investigated in this way, one had consistent dynamical and theoretical system mass estimates. Of the remaining three systems, each had a dynamical mass significantly lower than that predicted from the models. While this discrepancy may be indicative of a true divergence between the models and observations, the lack of metallicity measurements for these systems provide another explanation. Future orbital monitoring observations of A-star binary systems will provide further refinement to the orbital parameters and, combined with refinement of the magnitude, metallicity, and parallax measurements, will improve the analysis performed within this study.

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