ASSESSING SPECTROSCOPIC-BINARY MULTIPlicity PROPERTIES USING ROBO-AO IMAGING

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Abstract

We present higher-order multiplicity results for 60 solar-type spectroscopic binaries based on 0.75μm imaging data taken by the Robotic Adaptive Optics system (Robo-AO) at the Kitt Peak 2.1m telescope. Our contrast curves show sensitivity of up to ~5 mag at ~1″ separation. We find tertiary companions for 62% of our binaries overall, but find this fraction is a strong function of the inner binary orbital period; it ranges from ~47% for P_{bin} > 30d to as high as ~90% for P_{bin} < 5d. We similarly find increasing tertiary companion frequency for shorter period binaries in a secondary sample of Kepler eclipsing binaries observed by Robo-AO. Using Gaia distances, we estimate an upper limit orbital period for each tertiary companion and compare the tertiary-to-binary period ratios for systems in the field versus those in star-forming regions. Taken all together, these results provide further evidence for angular momentum transfer from three-body interactions, resulting in tight binaries with tertiaries that widen from pre-main-sequence to field ages.

1. INTRODUCTION

Although many of the underlying mechanisms and outcomes of the star-formation process remain under debate, the prevalence of stellar multiplicity is undisputed, with more than half of all stars having at least one companion. In the past decade, stellar multiplicity studies (e.g., Raghavan et al. 2010; Sana et al. 2014; Tokovinin 2014a; Fuhrmann et al. 2017) have focused on volume-limited samples in distinct spectral-type ranges to achieve unbiased statistical inferences of multiple systems. Others (e.g., Rucinski et al. 2007; Riddle et al. 2015; Hillenbrand et al. 2018) have used high-resolution, adaptive-optics imaging to identify and characterize new systems.

In particular, high spatial resolution campaigns at longer wavelengths have the ability to maximize detections of faint distant companions. Tokovinin et al. (2006) surveyed 165 solar-type spectroscopic binaries (SBs) and found that virtually all (~96%) short-period binary systems (P_{bin} < 3d) had tertiary companions.

This seminal finding has motivated a number of follow-on studies to explore the potential effects of, as well as the evolutionary pathways of, binaries in tertiary systems. The dynamics introduced by tertiaries could have significant consequences for the evolution of young stellar objects. For example, in the most recent review of benchmark pre-main-sequence (PMS) eclipsing binaries (EBs), Stassun et al. (2014) found that the properties of those in triple systems constituted the most highly discrepant cases when compared to PMS stellar evolution models, which may be explained if the tertiary inputs significant energy into one or both binary stars during periastron passages (see, e.g., Gómez Maqueo Chew et al. 2019).

More generally, the dominant physical mechanism by which the tertiary influences the creation of tightly bound binaries has not yet been established. Lidov-Kozai cycles with tidal friction (KCTF; Eggleton & Kiseleva-Eggleton 2001) have been hypothesized but require a long dynamical timescale and only operate for certain mutual orbital inclinations. Thus, KCTF is suspected to only be capable of producing a fraction of the total known population of close binaries.

Recent simulations of newborn triple systems (e.g., Reipurth & Mikkola 2012) have found binary orbital hardening occurring early in the systems’ evolution, whereby compact triple systems dynamically unfold into wider hierarchical structures. In this scenario, triple systems find themselves in the tight binary – wide tertiary configuration well before evolving onto the main-sequence. These findings have been corroborated by recent population synthesis work (e.g., Moe & Kratter 2018), which found ~60% of close binaries form in this manner, with additional energy dissipation arising from primordial gas-disk interactions in the binary.

Making progress in determining the respective rates of these different mechanisms requires a greater number of binary-star systems with well known periods, distances, and ages, and for which the presence of a tertiary companion is well established. In addition, the fundamental result of an increased tertiary occurrence among the tightest binaries (Tokovinin et al. 2006) should ideally be reproduced with independent samples, given its importance in motivating and constraining these questions.

In this paper, we seek to test the reproducibility of the cornerstone result of Tokovinin et al. (2006) and explore the evidence of potential evolutionary pathways for triple systems. In Section 2, we describe our sample of observed binaries and list some of their fundamental physical properties. We also describe the source and nature of our data along with data reduction and processing procedures. In Section 3, we describe our search for additional companions to our sample using published catalogs and with Gaia DR2, in some cases offering additional confirmation of our Robo-AO multiplicity identifications. In Section 4, we report the results of our Robo-AO SB multiplicity survey and compare with complementary Robo-AO observations of Kepler EBs. In Section 5, we discuss the implications of our results on current star-formation
and binary-evolution theory. Finally, in Section 6, we conclude with a brief summary of our findings.

2. DATA AND METHODS

2.1. Spectroscopic Binary Star Samples Used

The goals of this study include examining multiplicity fractions as a function of inner binary period and comparing the derived properties of our identified binaries with known multiples from the literature. Therefore, our Robo-AO target list required a large sample of spectroscopic binaries (SBs) with known orbital periods and distances. To this end, we use the Troup et al. (2016) sample of main-sequence Apache Point Observatory Galactic Evolution Experiment (APOGEE) stars identified with stellar and substellar companions, which includes 178 systems within 1 kpc. In addition, we also include the Torres et al. (2010) sample of benchmark eclipsing binaries (EBs which are also SBs). These 94 systems have known orbital periods and distances (Stassun & Torres 2016) as well as component masses and radii derived to an accuracy of 1–3%.

These two samples constitute the master list of SBs in our Robo-AO survey, of which we have observed 33 EBs from the Torres et al. (2010) sample and 43 targets from the Troup et al. (2016) sample, with orbital periods of the combined sample spanning the range 0.3–1880 d. Although all 43 Troup sources are radial velocity variable, we verify a clean sample of SBs by requiring the derived minimum mass of the companion to be greater than that of a brown dwarf (0.013M⊙). We also conservatively require the significance of the RV variations in sigma units to be greater than 10. This identifies 27 Troup et al. (2016) stars in our analysis in Sections 3 or 4, but for the benefit of future studies we report any companions that we identify in our Robo-AO imaging in Table 5. All of the targets in our sample have parallaxes reported in the Gaia second data release (DR2) with distances in the range 40–2200 pc. Graphical summaries of some basic parameters for our Robo-AO SB sample are displayed in Figure 1. Their properties and identifications are listed in Table 1.

For an independent test sample, we also made use of the published Robo-AO observations of Kepler EBs from Law et al. (2014), originally drawn from the master sample of Kepler objects of interest (KOIs). To enable a direct comparison with our Robo-AO sample, we trim the initial sample of 1065 KOI EBs as follows. To remove potential EB false positives, we required a minimum primary eclipse depth of 1 mmag, as fit by the Kepler EB pipeline’s polyfit algorithm (Prša et al. 2008). Similarly, we also required all systems to have a successful “morphology” classification (between 0 and 1) as output by the Local Linear Embedding (LLE) of the Kepler EB pipeline (Matijević et al. 2012). We excluded all targets fainter than the faint limit of our sample (V < 12.5) by converting their Kepler magnitudes to V via the published Kepler color-temperature relation. This also requires the EBs to have nominal effective temperatures listed in the Kepler Input Catalog. This leaves a remaining sample of 109 KOI EBs. Of these 109, 52 have Robo-AO observations, of which

Figure 1. Representative histograms of stellar properties for the Robo-AO SB sample (unfilled) and the subset with identified tertiary companions (filled). We note the mass histograms refer to binary mass except for our Troup et al. (2016) sources, which only have known mass values for the primary. The bias against detection of very low-mass companions (lower-right panel) is a reflection of the sensitivity limit of our data for faint sources (lower-left panel).

2.2. Robo-AO Imaging

Robo-AO is an autonomous laser adaptive optics system stationed at the Kitt Peak 2.1m Telescope from November 2015 to June 2018. Robo-AO has a field size of 360’’ on a side with a pixel scale of 35.1 milli-arcsec per pixel (Jensen-Clem et al. 2017). High spatial resolution images of the target stars were taken between November 2017 and June 2018. We observed 76 unique targets in the i’ bandpass (6731 - 8726Å) with 90-s exposures. Over the 90 second exposure, about 773 individual frames are generated. Target images were initially processed with the Robo-AO “bright star” pipeline as described in Law et al. (2014).

While this pipeline was appropriate for the majority of our Robo-AO SB images, we note five faint SB systems (2MASS IDs: J07381910, J16515260, J19301035, J19305116, and J19412976) that were not properly reduced. As noted in Jensen-Clem et al. (2017), the images in these cases failed to correctly center the PSF, leading to a single noticeably bright pixel in the center of the image. We remove these targets from the sample to avoid biasing our multiplicity analysis in Section 4, leaving 55 SBs. To maximize our detection of tertiaries at small angular separations, the images were further processed by the “high contrast imaging” pipeline described
in Jensen-Clem et al. (2017).

This pipeline first applies a high-pass filter on a 3′5 frame windowed on the star of interest to lessen the contribution from the stellar halo. A synthetic point spread function (PSF) is then subtracted, generated via Karhunen-Loève Image Processing (KLIP, a principal component analysis algorithm that whitens correlated speckle noise; Soummer et al. 2012). A representative sample of PSF diversity is achieved using a reference library of several thousand 3′5 square high pass filtered frames that have been visually vetted to reject fields with more than one point source. This technique of Reference star Differential Imaging (RDI; Lafrenière et al. 2009) results in the final PSF-subtracted image, from which we make our multiplicity determinations.

Measurement of multiple star systems position angles and separations also require a precise astrometric solution for the optical instrument. Nightly observations of densely populated globular clusters are used to establish and update this solution as described in Section 6 of Jensen-Clem et al. (2017). After each science target is fully reduced, the pipeline also produces a 5σ contrast curve by simulating companions and properly correcting for algorithmic throughput losses using the Vortex Image Processing (VIP) package (Gomez Gonzalez et al. 2017). Examples of our Robo-AO images pre- and post-processing, along with their corresponding contrast curves, are shown in Figure 2.

The expected Robo-AO error budget and performance is summarized in Table 2 of Jensen-Clem et al. (2017). At our observed Strehl ratios of a few percent, we expect a delivered FWHM of ∼0′′15. The majority of our SB sample have unambiguous detections or non-detections of a tertiary companion upon visual inspection of their PSF subtracted images. We assign these cases a multiplicity flag of “T”, or ”B” for cases of undetected companions.. In a small number of cases, we observe residuals that weakly imply a quadruple but are suspected to be artifacts from the PSF-subtraction process. We assign these cases a multiplicity flag of “T(Q?)” in Figures 8–10. Lastly, three cases have difficult to interpret residuals for which we are unable to determine identifications for (Figure 2, lower right) and are thus assigned a multiplicity flag of “U”. Our analysis in Section 4 excludes all unclear cases, resulting in a remaining sample of 52 SBs.

We do not resolve individual components at the raw image level for the majority of our Robo-AO observations (Figure 8–10). Many of the triples revealed in the PSF-subtracted images, however, show clear elongation compared to the point-source like observations of SBs with no detected companions. While the residuals from this process allow us identify the presence of a companion, it cannot be used to reliably measure flux contrasts. For each identified tertiary, we only measure an upper limit to its angular separation and a position angle by measuring the positions of the two peaks (i.e., the central unresolved SB and the tertiary companion) in the PSF subtracted images, carefully accounting for the slight difference in x and y pixel scales (noted in the appendix of Jensen-Clem et al. 2017). These are then translated into physical upper limit projected separations using the Gaia DR2 distance to each system. We note the masses for each target have been sourced from the literature and correspond to the binary mass, except for our Troup et al. (2016) sources, which only have known mass values for the primary. These masses are used to derive a rough upper limit estimate of the tertiary period. We report its logarithm along with our measured angular and projected separations for all of our multiple systems in Table 3. We note that our period estimates, however, can sig-

### Table 1
Robo-AO SB Sample

| Name            | R.A. (deg) | Dec. (deg) | P$_{bin}$ (d) | V (mag) | Multiplicity Flag | Sample ID       |
|-----------------|------------|------------|---------------|---------|-------------------|-----------------|
| V432 Aur        | 84.38524   | 37.08689   | 3.082         | 8.05    | T                 | Stassun & Torres - EB |
| WW Aur          | 98.11313   | 32.45482   | 2.525         | 5.82    | T                 | Stassun & Torres - EB |
| HS Aur          | 102.82702  | 47.67335   | 9.815         | 10.05   | B                 | Stassun & Torres - EB |
| HD 71636        | 127.48465  | 37.07095   | 5.013         | 7.90    | U                 | Stassun & Torres - EB |
| KX Cnc          | 130.69238  | 31.86242   | 31.22         | 7.19    | B                 | Troup - SB      |
| 2MASS J10352794 | 158.86626  | 25.20971   | 25.09         | 9.73    | B                 | Troup - SB      |
| 2MASS J11452973 | 176.3738   | 1.99299    | 1033.875      | 9.96    | B                 | Troup - SB      |

Note. — The full table is available in the electronic version of the Journal. A portion is shown here for guidance regarding its form and content.

* Multiplicity flag: B = binary, T = triple, U = undetermined (Section 2.2).
* Sample ID: Stassun & Torres - EB = EBs from Stassun & Torres (2016); Troup - SB = SBs from Troup et al. (2016)

### Table 2
Robo-AO KOI EB Sample

| KOI  | R.A. (deg) | Dec. (deg) | P$_{bin}$ (d) | V (mag) | Multiplicity Flag | Sample ID       |
|------|------------|------------|---------------|---------|-------------------|-----------------|
| 5774 | 283.86634  | 47.22828   | 2.4275        | 10.834  | T                 |                 |
| 5993 | 285.14501  | 39.18703   | 4.2647        | 13.0    | T                 |                 |
| 971  | 286.01929  | 48.86777   | 0.5331        | 7.642   | B                 |                 |
| 6109 | 287.83336  | 39.22124   | 22.9135       | 11.911  | T                 |                 |
| 1728 | 288.97163  | 44.62456   | 12.7319       | 12.069  | B                 |                 |
| 2758 | 289.74253  | 39.26713   | 253.3623      | 12.168  | B                 |                 |
| 1661 | 290.73807  | 39.91969   | 1.8955        | 11.601  | T                 |                 |

Note. — The full table is available in the electronic version of the Journal. A portion is shown here for guidance regarding its form and content.

* Multiplicity flag: B = binary, T = triple.
nificantly vary from the true period in cases where the projected separation is much different than the true semi-major axis of the system.

The resolution and sensitivity limits of our Robo-AO observations hinder our ability to detect long period ($P_3 \gtrsim 10^4$ yr) tertiaries. The 3.5 arcsec frame centered on each of our sources corresponds to a maximum detectable angular separation of 1.75 arcsec. For a typical tertiary in our sample, this corresponds to a tertiary period of $\sim 9200$ yr. Thus, very long period ($P_3 \gtrsim 10^4$ yr) tertiaries generally do not fall within our Robo-AO field of view.

3. CATALOG SEARCH FOR ADDITIONAL COMPANIONS

As the most sensitive probe of parallaxes and proper motions, Gaia provides a powerful opportunity to search more comprehensively for additional companions to our Robo-AO SB sample. Resolved common proper motion (CPM) companion matches have the ability to corroborate, or in some cases refine, our prior multiplicity determinations. Additionally, astrometric quality information of unresolved companions can similarly serve to confirm Robo-AO-identified multiples. As a final companion check, we also query the WDS catalog for prior multiplicity information on our Robo-AO targets.

3.1. Gaia Common Proper Motion Candidates

We begin by crossmatching our Robo-AO SBs with the Gaia DR2 catalog to obtain both parallax and proper motion information for each target. We then query Gaia DR2 to list all targets found within a 5 arcmin aperture centered on each Robo-AO binary. The aperture size chosen searches for any wide companions outside of our 3.5 arcsec Robo-AO field of view while minimizing those with separations that are unlikely to be bound. For both this larger sample as well as our Robo-AO-Gaia crossmatch, we apply the suggested corrections to the published Gaia DR2 magnitudes following Evans et al. (2018) and Maíz Apellániz & Weiler (2018), depending on the magnitude range considered. For the brighter ($G < 11.5$) stars in both samples, we also apply a proper motion correction due to the inertial spin of the Gaia DR2 proper motion system (Lindegren 2018).

Our wide search returns 49343 sources, 6810 of which do not have parallax or proper motion information. With the remaining 42533 sources, we follow a similar procedure to the Gaia companion candidate cuts chosen by Jiménez-Esteban et al. (2019) to find wide co-moving binaries. In our case, we choose more lenient fractional error cuts on parallax (20%) and proper motion (50%) to maximize our chances of identifying fainter companions while still ensuring reasonably high quality measurements. This vetting reduces the total number of candidate companions to 5332.
agree within 2.5σ of our derivations. We also report a faint (G ∼ 18.9) companion to BK Peg at an angular separation of 119″.1. We change their multiplicity designations from binary to triple.

Lastly, we return to the subsample of 7108 sources that Gaia does not record parallax or proper motion information for. Although these sources cannot be vetted for association, we check for those that have separations from their Robo-AO counterpart near Gaia’s resolution limit of 1″. We find one match to 2MASS J12260547+2644385, a confirmation of the wide (∼1″) triple companion confirmed in our Robo-AO imaging. Considering the other Robo-AO system with a relatively wider companion in the Robo-AO field of view, we find the (∼1″) triple companion for CG Cyg is not detected by Gaia. However, considering the proximity to Gaia’s resolution limit as well as the rarity of chance alignments at these separations, we choose to leave its multiplicity designation unchanged.

### 3.2. Gaia Astrometric Candidates

Significant deviations from Gaia’s astrometric fit, manifesting as large values of the Astrometric Goodness of Fit in the Along-Scan direction (GOF_AL) and the significance of the Astrometric Excess Noise (D), hint at the presence of unresolved companions. In particular, Evans
Astrometric Noise [mas]

0.2

0.8

Gaia

In this regime, if they do not possess an identified tertiary companion.

Robo-AO SB targets have entries and describe them individually below.

dividually below.

separates our tighter (left) and wider (right) Robo-AO SBs.

for systems which pass our astrometric criterion. The dashed line denotes the minimum astrometric noise observed for systems whose central SBs are tighter than ≲ 1.5 mas, right of dashed line) register significant astrometric noise (threshold marked by the dotted line). For those that do register astrometric noise in this regime, we find all (10) systems also have a companion identified in our Robo-AO imaging. We conclude that systems whose central SBs are tighter than ~1.5 mas are not noticed as multiples by Gaia, unless they also possess a wider tertiary.

In contrast, we find the vast majority (12/14) of our wider SBs (≫ 1.5 mas, right of dashed line) register significant astrometric noise values (above dotted line), even if they do not possess an identified tertiary companion. In this regime, Gaia is likely detecting the photocenter motion of the relatively wide SBs, regardless of whether there is a wider tertiary.

A similar analysis for our Robo-AO KOI EB sample also confirms our tertiary designations. The sole exception is KOI 6016, for which Gaia identifies significantly high values of GOF_AL = 166 and D = 2095. Assuming a total binary mass of 2 M☉, we estimate the angular separation of the EB (0.677 mas) to be much smaller than its measured astrometric excess noise (2.38 mas), thus we argue its source is an unresolved tertiary companion. We change its designation from binary to tertiary.

Figure 3. Gaia recorded astrometric noise for our Robo-AO SBs as a function of inner binary separation. Systems that (do not) pass our Gaia astrometric criterion (GOF_AL > 15 and D > 3) are shown in blue (orange). Filled (unfilled) dots correspond to cases where our Robo-AO imaging (did not) identified a companion within 3.9″. The dotted line denotes the minimum astrometric noise observed for systems which pass our astrometric criterion. The dashed line separates our tighter (left) and wider (right) Robo-AO SBs.

3.3. Washington Double Star Catalog Comparison

In this section, we carefully compare our observations to those listed in the WDS catalog. We find 8 of our Robo-AO SB targets have entries and describe them individually below.

2MASS J11480818+0138132 — The most recent companion identification listed in WDS entry 11482+0136 refers to observations in 2015 by the Garraf Astronomical Observatory (OAG). Its CPM wide pairs (WP) survey identified a V ≈ 11.1 companion at a separation of 119.1′′ with a position angle of 334°. While this target is outside of the field of view of our Robo-AO imaging, our Gaia CPM analysis (see Section 3.1) also identifies this wide companion.

2MASS J12260547+2644385 — WDS entry 12261+2645 refers to a singular speckle-interferometric observation that identified a V ≈ 9.7 companion at a separation of 1″ with a position angle (PA) of 167° (ASCN number 684901 in Guerrero et al. (2015)). Our Robo-AO observations find 2MASS J12260547+2644385 to be a triple, with a tertiary companion at an upper limit separation of 1″11 and a PA of 346°. Given our convention of measuring PA with respect to the SB (346°-180°=166°), we find these results to be in agreement and confirm this companion.

2MASS J16063131+2253008 — The most recent companion identification listed in WDS entry 16065+2253 refers to Pan-STARRS observations from 2015 as detailed by Deacon et al. (2014). They report a companion separation of 35″5 at a PA of 22°. The proposed source, 2MASS J16063229+2253337, is resolved by Gaia but faint (G ≈ 19.3). Gaia reports a parallax, R.A. proper motion, and Dec. proper motion of 11.734 ± 0.418 mas, −84.088 ± 0.538 mas/yr, and 90.03 ± 0.571 mas/yr. In comparison, Gaia reports 11.601 ± 0.075 mas, −88.263 ± 0.105 mas/yr and 72.873 ± 0.124 mas/yr for 2MASS J16063131+2253008. Given in particular the difference in Dec. proper motion, our Gaia CPM analysis does not find this pair to be associated.

2MASS J16074884+2305299 — The most recent companion identification listed in WDS entry 16078+2306 refers to a 2004 observation (Alam et al. 2015) that identified a V ≈ 13.3 companion at a separation of 12″2 with a position angle (PA) of 81°. A source at this separation does not fall into our Robo-AO field of view. Gaia resolves one other source within 15″, Gaia DR2 1206535963616734976, and reports a parallax, R.A. proper motion, and Dec. proper motion of 0.735 ± 0.02 mas, 3.58 ± 0.03 mas/yr, and −9.18 ± 0.03 mas/yr. In comparison, Gaia reports 2.04 ± 0.036 mas, −3.48 ± 0.04 mas/yr and −9.38 ± 0.05 mas/yr for 2MASS J16063131+2253008. These sources are clearly not physically associated.

V2368 Oph — WDS entry 17162+0211 refers to a singular 1985 speckle-interferometric observation from the Center for High Angular Resolution Astronomy (CHARA) (McAlister et al. 1987). They reported a separation of 0′′136 at a PA of 69°. As detailed in the auxiliary WDS notes, the WDS entry was recalled after repeated attempts at confirmation by McAlister but later restored. While the most recent effort to confirm this companion (Roberts & Mason 2018) was unsuccessful, our Robo-AO imaging detects a companion at an upper limit separation of 0′′175 at a PA of 68°. Given the close

1 The OAG CPMWP catalog can be found at https://www.oagarraf.net/Comunicaciones/OAG/CPM/GPX%20CATALOG%20EQUATORIAL%20ZONEN%202016_ASCII_1.0.txt.
agreement in separation and PA, we tentatively confirm this companion but encourage continued monitoring of this clearly complex case.

**V624 Her**— The most recent companion identification listed in WDS entry 17443+1425 refers to a 2015 Gaia DR1 observation (Knapp & Nanson 2018) that identified a V~11.75 companion at a separation of 40'' with a position angle (PA) of 151°. Gaia DR 2 reports a parallax, R.A. proper motion, and Dec. proper motion of 7.1119 ± 0.0628 mas, −2.271 ± 0.098 mas/yr, and 15.134 ± 0.096 mas/yr for V624 Her. In comparison, Gaia DR2 reports 0.7206±0.0457 mas, −0.446±0.074 mas/yr and −3.962±0.070 mas/yr for WDS 17443+1425B. These sources are clearly not physically associated.

**V478 Cyg**— The most recent companion identification listed in WDS entry 20196+3820 refers to a 2015 Gaia DR1 observation (Knapp & Nanson 2018) that identified a V~14.5 companion at a separation of 3°61 with a position angle (PA) of 258°. A source at this separation does not fall into our Robo-AO field of view. *Gaia* resolves one other source within 5'' of V478 Cyg but shows the pair to have discrepant parallaxes. We opt to retain our original identification.

**CG Cyg**— The most recent companion identification listed in WDS entry 20582+3511 refers to two speckle-interferometric observations in 2014 that identified a V~12 companion at a separation of 1''1 with a position angle (PA) of 358° (Horch et al. 2015). Our Robo-AO observations find CG Cyg to be a triple system, with a tertiary companion at an upper limit separation of 1''16 and a PA of 313°. Given the close agreement in separation and RA, we confirm this companion.

Given the faintness of the two wide companions we identified in Section 3.1 (G~19), it is not surprising the WDS catalog does not list entries for RT Crb or BK Peg. Similarly, the remaining 43 Robo-AO SBs do not have entries in the WDS catalog, likely a consequence of the difficulty of finding visual companions at the proximity of the (upper limit) separations of Robo-AO identified companions (<0''.25).

### 4. RESULTS

To summarize our analysis in Sections 2–3, out of our initial sample of 55 SBs, we obtain Robo-AO determinations in 52 cases. After our catalog search for additional CPM and astrometric candidate companions, we report a final tally of 20 binaries, 31 triples, and 1 quadruple system.

We begin by exploring the dependence of tertiary companion frequency on inner SB period for our Robo-AO SBs. Our 52 systems are sorted into SB period bins, with bin edges of 0, 3, 6, and 30 days (Figure 4, orange). Systems with periods greater than 30 d are grouped together (rightmost point). We find a trend of increasing incidence of tertiary companions toward shorter period SBs (orange points), with 90% of (3° < $P_{\text{bin}}$ < 6°) SBs having a tertiary companion compared to ~47% of the

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**Table 4**

| Period Bin | N | $f$ |
|------------|---|-----|
| $P_{\text{bin}} < 3$ | 12 | 0.75 ± 0.21 |
| $3 < P_{\text{bin}} < 6$ | 10 | 0.9 ± 0.25 |
| $6 < P_{\text{bin}} < 30$ | 11 | 0.45 ± 0.19 |
| $P_{\text{bin}} > 30$ | 19 | 0.47 ± 0.14 |

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The DSSC catalog can be found at [https://www.webbdeepsky.com/dssc/dssc23.pdf](https://www.webbdeepsky.com/dssc/dssc23.pdf)
Although there are only 10 KOI tertiaries among the SBs with $P_{\text{bin}} < 30^4$, we find general agreement between our Robo-AO results (Figure 4) and the KOI EB sample Figure 5. We again find a systematically higher fraction of tertiary companions with shorter period SBs, with both trends clearly consistent with the findings of Tokovinin et al. (2006). We again note this trend also seems to extend to binary periods of $P_{\text{bin}} > 30^4$.

**Figure 5.** Same as Figure 4, but for KOI EBs observed by Robo-AO (red). The final bin represents all SBs with $P_{\text{bin}} > 30^4$.

### 5. DISCUSSION

#### 5.1. Tertiary-to-Binary Orbital Period Ratios

The increasing number of known multiples with well-defined orbital periods has lead to a thorough probing of the distribution of tertiary orbital period as a function of inner binary period. In Figure 6, the large sample of known triples from the updated Multiple Star Catalog (MSC) (Tokovinin 2018) (grey crosses) and the smaller sample of triples from the volume-limited Raghavan et al. (2010) sample (black crosses) clearly indicate the wide range of permitted tertiary-binary period ratios. However, as noted in both Tokovinin (2014a) and Tokovinin (2018), the rarity of systems with small period ratios (< 10), and in particular short tertiary periods ($P_T < 10$ yr), is evident from the lack of points along the dynamical stability limit $P_T = 4.7P_1$ (solid line; Mardling & Aarseth 2001) in the lower left corner.

In an effort to explore a potential correlation with age, we refer to the benchmark PMS EB sample (Stassun et al. 2014), of which 7 of the 13 are identified with or have evidence of a tertiary companion. Three of these systems (RS Cha, TY CrA, and MML 53; Woollands et al. 2013; Corporon et al. 1996; Gómez Maqueo Chew et al. 2019) have tertiaries with orbital solutions; their ages range from 3–15 Myr. A literature search for additional PMS tertiaries also reveals orbital solutions for V1200 Cen (Coronado et al. 2015), GW Ori (Czekala et al. 2017), TWA 3A (Kellogg et al. 2017), V807 Tau (Schaefer et al. 2012), as well as TIC 167692429 and TIC 220397947 (Borkovits et al. 2020).

The tendency for these PMS systems to lie at low tertiary-binary period ratios is evident in Figure 6. To probe the potential significance of this apparent difference relative to the older field population, we perform a two-dimensional, two-sided KS test between the PMS sample and the volume-limited Raghavan et al. (2010) sample, reporting a $p$-value < $10^{-4}$. The difference is statistically significant, which corroborates the visual impression that indeed the PMS sample occupies a different distribution of tertiary-to-binary orbital periods than the field-age sample.

For our Robo-AO sample, we note the upper limits of our estimated tertiary periods (red and yellow arrows in Figure 6) are consistent with the larger field-age samples of Tokovinin (2018) and Raghavan et al. (2010).

**Figure 6.** Estimated tertiary periods as a function of inner binary period. Identified Robo-AO triples are marked as red (Torres et al. 2010) and orange (Troup et al. 2016) arrows, given our estimates are upper limits. For comparison, we plot the updated MSC triples (Tokovinin 2018) as grey crosses while overplotting the triples from the volume-limited Raghavan et al. (2010) sample as black crosses. For reference, the dashed line represents $P_T = 10^{1.5}P_1$. The dynamical stability limit for triples ($P_T = 4.7P_1$) is shown by the full line. Known PMS (≤30 Myr) triples are shown in blue.

#### 5.2. Hierarchical Unfolding

Although tertiary-induced inner binary period shortening is evident, there is growing evidence that a single mechanism, such as Lidov-Kozai cycles with tidal friction (KCTF), cannot recreate the entire population of known close binaries (e.g., Kounkel et al. 2019; Bate 2019). As has already been shown for individual cases (e.g., Gómez Maqueo Chew et al. 2019), we find that many of the well-characterized EBs in young (<30 Myr) triple systems have already achieved close separations (≤0.1 AU). Evolution by the KCTF mechanism, which has an effective timescale on the order of ~100 Myr, is unable to account for these (<30 Myr) systems.

The alternative mechanism of hierarchical unfolding (e.g., Reipurth & Mikkola 2012), in which the orbit of a newly bound wide (100–1000 AU) binary is shrunk by ejecting a third body into a distant orbit, is unable to achieve the close separation of a spectroscopic binary alone. However, because these interactions often result in a highly eccentric orbit for the binary, the additional dissipative interactions with the primordial gas expected in the disks of these young binaries also aid in the observed orbital evolution. Recent population synthesis work (Moe & Kratter 2018) finds that ~60% of close binaries ($P_{\text{bin}} < 10^6$) form during the PMS phase and in a compact configuration with a tertiary companion as a
Known PMS triples with estimated orbits are notably compact and weakly-hierarchical, with significantly smaller tertiary-to-binary period ratios than the majority of known triples in the field (see Figure 6). The majority of our Robo-AO triples with known ages (12/15) are field-age (~1 Gyr) systems, and have thus had sufficient time to dynamically evolve. In comparison to the PMS systems, they all lie in the cluster of points with upper limit period ratios of $10^{3.5}$ or greater. Although it is not feasible to reconstruct the dynamical pathway taken by each system, as both hierarchical unfolding and KCTF are able to account for the current orbital configurations, their hierarchical nature is evident, with a range of hardened inner binaries ($P_{\text{bin}} < 30^3$) and large tertiary-to-binary period ratios ($\geq 10^{3.5}$).

This apparent difference between the field-age and PMS sample could be equally explained from the standpoint of the tertiary companion or the inner binary. The simulations of Reipurth & Mikkola (2012) find the most extreme wide systems take on the order of ~100 Myr to fully unfold and thus it is possible some of the tertiaries in these PMS systems still have significant dynamical evolution to undergo. Alternatively, if the reservoir of primordial circumstellar disk gas is not yet exhausted, it is possible some of our PMS binaries are still in the process of hardening if young enough. Thus, the conditions for evolution via hierarchical unfolding with dissipative gas interactions appear to be in place for the youngest systems.

Another question is whether the dynamical evolution of triple systems leads to tertiaries that are wider than would be expected to arise from the formation process alone. Tokovinin (2014b) argued that overall distributions of inner and outer orbital periods in multiple-star systems is consistent with dynamical sculpting that produces inner binaries populating the short-period part of the overall distribution and outer companions populating the long-period part of the overall distribution. But is there evidence that tertiaries come to reach wider separations than the widest binaries? To this end, we compare the period distributions of simple binaries versus triples within the volume-limited Raghavan et al. (2010) and Tokovinin (2014a) samples (Figure 7).

The upper bound of the appropriate period range for the comparison considers the longest period for which both binaries and tertiaries are observed (~$10^7$ years). Because inner binaries of triple systems cannot be as wide as their tertiaries, we do not extend the lower bound to the period for which the tightest tertiaries are observed (10 years); instead, we consider the longest period binaries in the triples identified in the larger volume-limited sample of Tokovinin (2014a). We choose a generous lower bound of $10^3$ years, with only a small number of binaries (identified through CPM) exceeding this period.

Within this period range ($10^3 < P < 10^7$ years), we perform a two-sample Anderson-Darling test on the lone Tokovinin binaries versus tertiaries (dotted distributions in Fig. 7) to probe the differences in the tails of these distributions. We do not find strong evidence (p-value $= 0.06$) that tertiary companions find themselves at wider separations than their simple binary counterparts. We find a similar result when considering the Raghavan sample (solid distributions in Fig. 7). There is therefore not strong evidence to suggest that the mechanisms governing the underlying populations of the widest binaries and tertiaries are distinct, consistent with the findings of Tokovinin (2014b).

6. SUMMARY

In this paper, we have conducted robotic adaptive optics (Robo-AO) imaging for a sample of 60 spectroscopic binaries (SBs) with known periods and distances. For 52 individual sources, we identify companions, or lack thereof, through a visual inspection of their PSF subtracted images and search for additional candidates using Gaia parallaxes, proper motion, and astrometric information. Overall, we identify 31 tertiary systems and 1 quadruple systems.

A principal aim of this paper was to test the reproducibility of the canonical result from Tokovinin et al. (2006), namely that tertiary frequency is a strong function of inner binary orbital period. For our Robo-AO identified tertiaries, we find higher fractions of tertiary companions around shorter period binaries, with 75% of P_{\text{bin}} < 3^d systems having a tertiary companion compared to ~47% of the longest period (P_{\text{bin}} > 3^d) systems, consistent with the findings of Tokovinin et al. (2006) and extending that result to even longer-period inner binaries. A separate test sample of the smaller number of Robo-AO observed KOI EBs also shows this trend. The two samples, thus, appear to independently reproduce the canonical result of Tokovinin et al. (2006).

We have roughly estimated the tertiary period for each of our triples, exploring the dependence of their distributions on inner SB period and age. Although we are unable to determine the prominent mechanism at work for their dynamical evolution, we note all of our field-age Robo-AO triples find themselves in hierarchical configurations, with large (P_3/P_1 > $10^{3.5}$) tertiary-binary period ratio upper limits. In comparison, we find known young PMS triples are much more compact in comparison, with the conditions for hierarchical unfolding (e.g., Reipurth & Mikkola 2012) already in place. We find these results to be consistent with the recent population synthesis predictions of Moe & Kratter (2018).
Taken together, the results of this investigation can be interpreted through a framework in which stellar triples evolve from relatively compact configurations to increasingly hierarchical configurations, in which the hardest binaries arise almost exclusively through tertiary interactions, and in which the widest tertiaries arise through interactions with their inner binaries.

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**REFERENCES**

Alam, S., Albareti, F. D., Allende Prieto, C., et al. 2015, ApJS, 219, 12, doi: 10.1086/650479/219/1/12

Artymowicz, P., Clarke, C. J., Lubow, S. H., & Pringle, J. E. 1991, ApJ, 370, L35, doi: 10.1086/185971

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33, doi: 10.1051/0004-6361/201322068

Baranec, C., Ziegler, C., Law, N. M., et al. 2016, AJ, 152, 18, doi: 10.3847/0004-6262/152/1/18

Bate, M. R. 2019, Monthly Notices of the Royal Astronomical Society, 484, 2341, doi: 10.1093/mnras/stz103

Borkovits, T., Rappaport, S. A., Hajdu, T., et al. 2020, MNRAS, doi: 10.1093/mnras/staa495

Coronado, J., Helminia, K. G., Vanzi, L., et al. 2015, Monthly Notices of the Royal Astronomical Society, 448, 1937, doi: 10.1093/mnras/stv010

Corporon, P., Lagrange, A. M., & Beust, H. 1996, A&A, 310, 228

Czekala, I., Andrews, S. M., Torres, G., et al. 2017, ApJ, 851, 132, doi: 10.3847/1538-4357/aa9b6

Deacon, N. R., Liu, M. C., Magnier, E. A., et al. 2014, ApJ, 792, 119, doi: 10.1088/0004-637X/792/2/119

Eggleton, P. P., & Kiseleva-Eggleton, L. 2001, The Astrophysical Journal, 562, 1012, doi: 10.1086/323443

Eker, Z., Soydugan, F., Soydugan, E., et al. 2015, The Astronomical Journal, 149, 131, doi: 10.1088/0004-6262/149/4/131

Evans, D. F. 2018, Research Notes of the American Astronomical Society, 2, 20, doi: 10.3847/2515-5172/aac173

Evans, D. W., Riello, M., De Angelis, F., et al. 2018, A&A, 616, A4, doi: 10.1051/0004-6361/201832756

Fuhrmann, K., Chini, R., Kaderhandt, L., & Chen, Z. 2017, The Astrophysical Journal, 836, 139, doi: 10.3847/1538-4357/836/1/139

Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al. 2016, A&A, 595, A1, doi: 10.1051/0004-6361/201629272

Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, A&A, 616, A1, doi: 10.1051/0004-6361/201833051

Gomez Gonzalez, C. A., Wertz, O., Absil, O., et al. 2017, AJ, 154, 7, doi: 10.3847/1538-3881/aa7367

Gómez Maqueo Chew, Y., Hobb, L., Stempels, H. C., et al. 2019, Astronomy & Astrophysics, 623, A23, doi: 10.1051/0004-6361/201832999

Guerrero, C. A., Oroz, V. G., Monroy-Rodriguez, M. A., & Borges Fernandez, M. 2015, AJ, 150, 16, doi: 10.1088/0004-6256/150/1/16

Hillenbrand, L. A., Zhang, C., Riddle, R. L., et al. 2018, The Astronomical Journal, 155, 51, doi: 10.3847/1538-3881/aaa01e

Horch, E. P., van Belle, G. T., Davidson, James W., et al. 2015, AJ, 150, 151, doi: 10.1088/0004-6256/150/5/151

Hunter, J. D. 2007, Computing In Science & Engineering, 9, 90

Jensen-Clem, R., Duev, D. A., Riddle, R. L., et al. 2017, The Astronomical Journal, 155, 32, doi: 10.3847/1538-3881/aa9be6

Jiménez-Esteban, F. M., Solano, E., & Rodríguez, C. 2019, AJ, 157, 78, doi: 10.3847/1538-3881/aafacc

Joye, W. A., & Mandel, E. 2003, in Astronomical Society of the Pacific Conference Series, Vol. 295, Astronomical Data Analysis Software and Systems XII, p. 489

Kellogg, K., Prato, L., Torres, G., et al. 2017, ApJ, 844, 168, doi: 10.3847/1538-4357/aa7c60

Knapp, W., & Hanson, J. 2018, Journal of Double Star Observations, 14, 503

Kounkel, M., Covey, K., Moe, M., et al. 2019, The Astronomical Journal, 157, 196, doi: 10.3847/1538-3881/aab3b1

Laferrière, D., Marois, C., Doyon, R., & Barman, T. 2009, ApJ, 694, L148, doi: 10.1088/0004-637X/694/2/L148

Law, N. M., Morton, T., Baranec, C., et al. 2014, The Astrophysical Journal, 791, 35, doi: 10.1088/0004-637X/791/1/35

Lindegren, L. 2018, in IAU Symposium, Vol. 330, Astrometry and Astrophyics in the Gaia Sky, ed. A. Recio-Blanco, P. de Laverny, A. G. A. Brown, & T. Prusti. 2018, doi: 10.3847/2041-8213/aaa01e

Maži Apellániz, J., & Weiler, M. 2018, A&A, 619, A180, doi: 10.1051/0004-6361/201834051
### Table 5

**Robo-AO Non-SB Observations**

| Name | R.A. (deg.) | Dec. (deg.) | V (mag) | Strehl Ratio (%) | Multiplicity Flag³ |
|------|-------------|-------------|---------|------------------|---------------------|
| 2MASS J05130342+2423489 | 78.264217899 | 24.396841655 | 6.707 | 2.06 | T |
| 2MASS J08140761+3145095⁴ | 123.531723248 | 31.752562931 | 12.44 | 6.52 | B |
| 2MASS J08145689+3208572 | 123.736957886 | 32.149168567 | 8.3 | 4.51 | B |
| 2MASS J1004394+2348227 | 142.636911616 | 27.585936424 | 10.722 | 3.56 | N |
| 2MASS J100722+4415409 | 166.029847747 | 44.261378235 | 9.685 | 3.66 | B |
| 2MASS J1146736+3424349 | 176.69737612 | 34.409630054 | 10.378 | 2.14 | N |
| 2MASS J13312997+3813115 | 202.874932285 | 38.21983319 | 10.839 | 2.86 | N |
| 2MASS J13334365+3754543 | 203.431735917 | 37.915035417 | 10.219 | 1.96 | N |
| 2MASS J13392768+2726135⁴ | 204.864597905 | 27.437240111 | 11.777 | 6.72 | |
| 2MASS J15055682+2216202 | 226.486763946 | 22.27236675 | 8.71 | 3.36 | B |
| 2MASS J15120615+6826579 | 228.025462449 | 68.449601426 | 9.621 | 1.68 | N |
| 2MASS J16385624+3652029 | 249.734407561 | 36.867145444 | 10.311 | 2.72 | N |
| 2MASS J1720510+422016 | 260.208784546 | 42.38376309 | 10.75 | 3.87 | B |
| 2MASS J19303059+3751364 | 292.627494341 | 37.860165321 | 10.688 | 4.86 | B |
| 2MASS J19344300+4651099 | 293.6792058 | 46.852733735 | 7.768 | 1.26 | N |

³Multiplicity flag: B = binary, T = triple, N = no companion detected.

⁴Faint systems that were not reduced properly (see Section 2.1) (no companion information could be deduced from RoboAO imaging.)

### APPENDIX

**MOSAIC OF PSF-SUBTRACTED ROBOAO IMAGES**

To display the companions identified from our RoboAO imaging, we first show a mosaic of our pre-PSF-subtracted images for each SB system, followed by a mosaic of our PSF-subtracted images with visual aids pointing to each resolved companion.
Figure 8. Pre-PSF-subtracted images for RoboAO SBs (continued in Figure 9 and Figure 10). We note the designation in the top right corner of each image corresponds to that determined strictly by our RoboAO imaging and thus does not include the results of our wide companion identifications in Section 3. Our final identifications are that listed in Table 1.
Figure 9. Pre-PSF-subtracted images for RoboAO SBs (continued from Figure 8). We note the designation in the top right corner of each image corresponds to that determined strictly by our RoboAO imaging and thus does not include the results of our wide companion identifications in Section 3. Our final identifications are that listed in Table 1.
Figure 10. Pre-PSF-subtracted images for RoboAO SBs (continued from Figure 9). We note the designation in the top right corner of each image corresponds to that determined strictly by our RoboAO imaging and thus does not include the results of our wide companion identifications in Section 3. Our final identifications are that listed in Table 1.
Figure 11. PSF-subtracted images for RoboAO identified multiples (continued in Figure 12).
Figure 12. PSF-subtracted images for RoboAO identified multiples (continued from Figure 11).