The Astronomical Journal, 150:130 (7pp), 2015 October doi:10.1088/0004-6256/150/4/130

OBSERVATIONS OF HIERARCHICAL SOLAR-TYPE MULTIPLE STAR SYSTEMS

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Received 2015 March 25; accepted 2015 September 1; published 2015 September 30

ABSTRACT

Twenty multiple stellar systems with solar-type primaries were observed at high angular resolution using the PALM-3000 adaptive optics system at the 5 m Hale telescope. The goal was to complement the knowledge of hierarchical multiplicity in the solar neighborhood by confirming recent discoveries by the visible Robo-AO system with new near-infrared observations with PALM-3000. The physical status of most, but not all, of the new pairs is confirmed by photometry in the *Ks* band and new positional measurements. In addition, we resolved for the first time five close sub-systems: the known astrometric binary in HIP 17129AB, companions to the primaries of HIP 33555, and HIP 118213, and the companions to the secondaries in HIP 25300 and HIP 101430. We place the components on a color–magnitude diagram and discuss each multiple system individually.

Key words: binaries: visual – instrumentation: adaptive optics

1. INTRODUCTION

Statistics of binaries and hierarchical stellar systems trace conditions of star formation and serve as an excellent diagnostic for testing theoretical predictions and numerical simulations. Only recently have observational techniques such as adaptive optics (AO) and radial velocities (RV) reached the maturity and productivity needed for a high quality binary census over a wide range of periods. The latest results on binary statistics are reviewed by Duchêne & Kraus (2013).

Reaching completeness for triple and higher-order hierarchies is even more challenging. The fraction of known hierarchical systems in the nearby 25 pc volume has doubled recently (Raghavan et al. 2010) in comparison with the earlier work by Duquennoy & Mayor (1991). Large space volume and large samples are needed for their statistical study as the fraction of triples is only 14% (Tokovinin 2014b). However, observing thousands of targets by complementary techniques would require prohibitive amounts of telescope and calendar time unless an intelligent strategy is applied. As noted by Raghavan et al. (2010), new observations mostly convert binaries into triples. So, focusing on known binaries and quantifying the presence of additional components (hence hierarchies) is a productive approach. It was adopted in the massive multiplicity survey of solar-type stars conducted in 2012–2013 with the Robo-AO instrument at the Palomar 60 inch telescope (Riddle et al. 2015); hereafter R15. That survey looked for subsystems in the faint secondary components and for distant tertiary companions to known binaries with FG primaries within 67 pc. The full sample is described in (Tokovinin 2014a).

We report here the beginings of follow-up observations to the R15 survey at the Palomar 5 m telescope. Our goal is to both confirm the newly discovered subsystems with infrared (IR) imagery and to combine that IR imagery with the Robo-AO observations in i' band. Multi-color photometry allows us to place the secondaries on a color–magnitude diagram (CMD) to test their physical relation to the main target. For systems with high proper motion (PM), the second-epoch astrometry within a year allows discrimination between physical binaries and unrelated optical companions. This is most critical for wide binaries because the probability of interlopers is proportional to the square of the separation. However, many new pairs with separations on the order of 5″ also need confirmation, particularly near the Galactic plane where the density of stars is high. At this time, we have only been able to collect data on a portion of the companions detected in R15; future observations will cover the other systems.

Quite unexpectedly, observations with PALM-3000 resolved several subsystems missed by the Robo-AO instrument in R15 because their companions were either too close or too faint. The old rule about new techniques bringing new discoveries is once again verified.

The observations and data reduction are covered in Section 2. In Section 3 we derive individual magnitudes and colors of the components and place them on the CMD. Each multiple system is commented on in Section 4. Discussion and conclusions are in Section 5.

2. OBSERVATIONS

We observed the stars on 2013 September 28 UT with the Palomar Observatory Hale 5 m telescope using the PALM-3000 AO system and the PHARO near-IR camera. The PALM-3000 AO system is a natural guide-star system using two deformable mirrors (Dekany et al. 2013). One corrects low-amplitude high spatial frequency aberrations, while the other corrects the higher-amplitude low spatial frequency aberrations. It is optimized for high contrast observations and routinely produces Strehl ratios greater than 80% in *Ks* band. The PHARO camera uses a HgCdTe HAWAII detector for observations between 1 and 2.5 μm wavelength (Hayward et al. 2001). The camera has multiple filters in two filter wheels. The filter wheels contain spectral band filters and neutral density filters. These neutral density filters are used for observing bright stars, which saturated the detector. Unfortunately, both the 1% and the 0.1% ND filter cause ghost reflections which appear as stellar companions. These ghosts always appear in the same locations and during analysis they are considered to be part of the point-spread function.

Table 1
Astrometry and Photometry

WDS	HD	HIP	Discoverer	Epoch	θ (°)	ρ (″)	ΔJ	ΔKs
00487+1841	4655	3795	RAO 5 Ca,Cb	2013.8371	320.9 ± 1.0	0.66 ± 0.01	...	0.86 ± 0.02
01027+0908	6152	4878	RAO 39 AB	2013.8371	37.0 ± 0.5	2.81 ± 0.01	5.75 ± 0.20	5.20 ± 0.06
01075+4116	6611	5276	RAO 40	2013.8371	336.0 ± 0.7	6.16 ± 0.02	5.4 ± 0.2	4.75 ± 0.03
02462+0536	17250	12925	RAO 9	2013.8370	253.7 ± 0.6	1.89 ± 0.01	3.26 ± 0.05	2.63 ± 0.02
03390+4232	22521	17022	RAO 47	2013.8370	142.8 ± 0.6	1.76 ± 0.01	6.26 ± 0.83	5.74 ± 0.16
03401+3407[a]	22692	17129	RBR 26 Aa,Ab	2013.8370	44.0 ± 1.3	0.50 ± 0.01	4.2 ± 0.8	3.83 ± 0.26
03401+3407	22692	17129	STF 425 AB	2013.8370	60.8 ± 0.6	1.93 ± 0.01	0.16 ± 0.01	0.16 ± 0.01
03413+4554	22743	17217	RAO 48AC	2013.8370	269.3 ± 0.6	4.78 ± 0.03	...	4.78 ± 0.04
04363+5502	28907	21443	RAO 35	2013.8370	14.8 ± 0.7	5.71 ± 0.05	3.88 ± 0.07	3.04 ± 0.02
05247+6323	34839	25300	STF 677 A,Ba	2013.8370	117.9 ± 0.5	1.10 ± 0.01	...	0.57 ± 0.01
05247+6323[a]	34839	25300	RBR 27 Ba,Bb	2013.8370	68.0 ± 4.4	0.13 ± 0.01	...	1.25 ± 0.1
05247+6323	34839	25300	RAO 36 AC	2013.8370	227.0 ± 0.5	6.99 ± 0.01	...	4.35 ± 0.04
06335+4822	46013	31267	RAO 80 AC	2013.8371	222.8 ± 0.5	4.82 ± 0.01	4.20 ± 0.15	3.28 ± 0.02
06562+4032[a]	50720	33355	RBR 28 Aa,Ab	2013.8371	125.7 ± 0.6	1.50 ± 0.01	6.81 ± 0.8	6.07 ± 0.1
06562+4032	50720	33355	RAO 56 AC	2013.8371	158.0 ± 0.5	5.58 ± 0.01	6.02 ± 0.34	5.36 ± 0.06
17422+3804[a]	161163	86642	RBR 29 Aa,Ab	2013.8371	202.0 ± 1.0	0.08 ± 0.01	1.77 ± 0.10	1.36 ± 0.5
17422+3804	161163	86642	RAO 20 AB	2013.8371	302.2 ± 0.3	2.23 ± 0.01	4.07 ± 0.13	3.60 ± 0.03
19359+5659	185414	96395	RAO 87	2013.8371	251.3 ± 0.5	10.04 ± 0.02	4.63 ± 0.15	3.74 ± 0.03
20312+5653	195872	101234	RAO 22	2013.8367	163.8 ± 3.4	0.17 ± 0.01	2.48 ± 0.3	2.27 ± 0.18
20333+3323	195992	101430	HJ 1535 A,Ba	2013.8368	246.3 ± 0.5	17.05 ± 0.03	3.60 ± 0.05	2.87 ± 0.02
20333+3323[a]	195992	101430	RBR 29 Ba,Bb	2013.8368	294.5 ± 9.1	0.17 ± 0.03	0.09 ± 0.02	0.25 ± 0.04
20333+3323	195992	101430	RAO 71 AE	2013.8368	225.8 ± 0.5	12.13 ± 0.02	5.39 ± 0.2	4.60 ± 0.03
20577+2624	199598	103455	RAO 24	2013.8368	100.1 ± 1.0	0.66 ± 0.01	3.34 ± 0.50	2.79 ± 0.08
21102+2045	201639	104514	RAO 25	2013.8368	210.0 ± 0.5	3.28 ± 0.01	3.91 ± 0.07	3.33 ± 0.02
21585+0347	208776	108473	RAO 73	2013.8368	89.8 ± 0.5	12.35 ± 0.02	...	4.44 ± 0.03
23588+3156[a]	224531	118213	RBR 30 Aa,Ab	2013.8369	348.0 ± 2.2	0.41 ± 0.01	5.1 ± 1.0	4.40 ± 0.50
23588+3156	224531	118213	RAO 76	2013.8369	87.9 ± 0.5	4.84 ± 0.01	5.51 ± 0.25	4.83 ± 0.04
23588+3345	224543	118225	RAO 77	2013.8372	173.6 ± 0.6	5.05 ± 0.02	5.84 ± 0.21	5.25 ± 0.05

Note.
[a] New discovery.

Fifty frames were collected of each object with an exposure time of 1.416 s, the minimum exposure for PHARO. After the observing run, the individual frames were reduced by debiasing, flat fielding, bad pixel correction and background subtraction. Then we created five images by co-adding 10 frames into each image. Creating multiple images allowed us to evaluate the precision of the measurements. The *fitstars* algorithm was used to measure the astrometry and photometry of the objects (ten Brummelaar et al. 1996, 2000).

We observed six calibration binaries[5] on the same night as the science targets. We compared their measured astrometry with the ephemeris predicted from their orbits and used the results to compute the plate scale and the position angle offset, 24.9 ± 0.2 mas pixel^{-1} and 0°.7 ± 0°.5 error. The largest error term is the position angle offset. In speckle and AO work on binaries, the measurement errors in tangential and radial directions are usually the same or similar. For the position angle error bar, we quadratically added the position angle offset error with the product of one radian and the ratio of the measurement error to the measured separation. The separation error bar was computed simarily, with the measurement error summed quadratically with the product of the plate scale error and the separation. Photometric error bars were assigned using the technique described in Roberts et al. (2005). The resulting photometry and astrometry are presented in Table 1. The table gives the Washington Double Star (WDS; Mason et al. 2001) Catalog designation for the system as are the HD and HIP numbers for the primary star. This is followed by the discoverer designation, the observation epoch, the astrometry and the photometry. New discoveries are marked with a footnote to the WDS ddesignation.

[5] http://ad.usno.navy.mil/wds/orb6/orb6c.html

3. COLOR–MAGNITUDE DIAGRAM

Using the differential photometry in the *Ks* band from Table 1 and the i' band data from R15, we calculated the individual magnitudes of stellar components. The combined *J* and *Ks* magnitudes of close binaries were taken from the 2MASS. However, the SDSS i' magnitudes (Fukugita et al. 1996) are not available for all our targets. We interpolated them from the *J* and *V* magnitudes using the color index $c = V - Ks$ as argument. Taking as a template the 1 Gyr isochrone from the Dartmouth stellar models (Dotter et al. 2008), we approximated the color–color relations for dwarfs less massive than 1.5 $\mathcal{M}_\odot$ by quadratic polynomials

$$V - i' = -0.235 + 0.3103c + 0.02118c^2, \quad (1)$$

$$i' - J = 0.435 + 0.2354c + 0.02414c^2. \quad (2)$$

The two estimates of i' for our targets derived from *V* and *J* agree very well, with an rms difference of only 0.026 mag. We then averaged these estimates to get the combined i' magnitudes.

Figure 1 places primary and secondary components of multiple systems resolved both here and in R15 in the (i', $i' - Ks$) CMD. The *Hipparcos* parallaxes of the primary targets (van Leeuwen 2007) are used. The lines are the 1 Gyr isochrones for solar metallicity and [Fe/H] = −0.5 from the

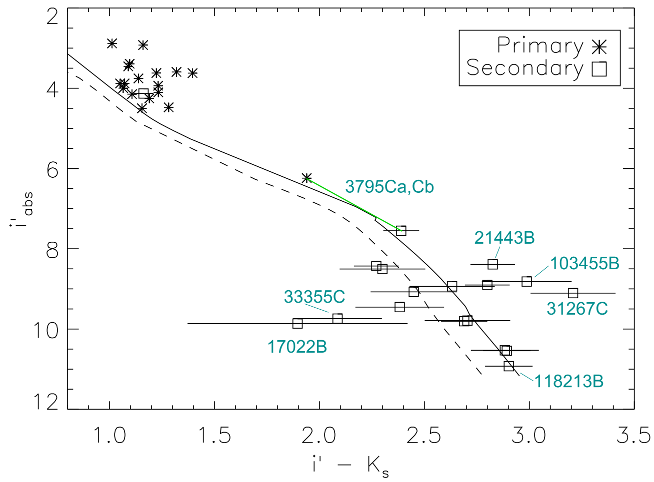

Figure 1. Color–magnitude diagram for the stars in this paper. The full and dashed lines show the 1 Gyr isochrones for solar metallicity and [Fe/H] = −0.5, respectively (Dotter et al. 2008). The green line connects the Ca and Cb components of HIP 3795. Some primary components undoubtably contain unresolved binaries. The *Hipparcos* names and binary star designations are listed for some of the points. See Section 4 for discussion of the individual systems.

Dartmouth stellar models (Dotter et al. 2008) retrieved from the web interface.[6] The errors of the color indices of secondary components are shown. They are computed by assuming realistic errors of the differential i'-band photometry in R15, typically $0\overset{\mathrm{m}}{.}1$, and combining them with the errors reported in Table 1. Note that all primary components (as well as other F- and G-type stars within 67 pc) are located above the main sequence (MS), indicating potential bias in the Dartmouth models. Some primaries are in fact close binaries.

4. COMMENTS ON INDIVIDUAL SYSTEMS

Stellar systems with three or more components require individual analysis. We provide below comments on each object, identified by the *Hipparcos* number of the primary component. The location of faint components on the CMD is used jointly with the astrometric information and field crowding to evaluate whether the binary is physical or optical (chance alignment). For some new pairs we compare in Table 2 the differential motion of the binary with the PM of the main target (van Leeuwen 2007). Differential astrometry from Table 1 is combined with the first epoch taken either from R15 (assuming positional errors of half a pixel or 22 mas when they are not listed) or from 2MASS (accuracy of $0\overset{''}{.}1$ is assumed). Columns (1) and (2) identify the pair by its *Hipparcos* number and components. The time difference Δt in Column (3) exceeds 10 years when the first epoch is taken from 2MASS. Columns (4) and (5) give the computed relative motion in right ascension and declination, while Columns (6) and (7) list the PM of the main target. Column (8) gives the number of 2MASS stars expected within the binary separation. These estimates do not take into account the brightness of the companion and the magnitude distribution of background sources, and are just a crude indication of the odds that a binary is optical. The last Column (9) summarizes the status of the companion (O for optical, P for physical, P? for likely physical, and ? for status unknown). Background stars usually have a small PM, and in such cases the differential PM is almost opposite to PM(A). On the other hand, a detectable relative motion can be orbital or can be caused by motions in inner subsystems and does not necessarily mean that the binary is optical.

For some of the systems, we estimated the orbital period, P, of the binary from the measured separations, ρ, distances, and mass sum $\mathcal{M}$ using *Kepler*'s Third Law, $\frac{a^3}{P^2} = \mathcal{M}$. The median ratio between the projected separation, $d \left(=\frac{\rho}{\pi_{\mathrm{HIP}}}\right)$, and orbital semimajor axis, a, is close to one (Tokovinin 2014a), with scatter by a factor of two caused by orbital phase, orbit orientation, and eccentricity. The strict lower limit is $a > \frac{d}{2}$. Statistical period estimates using the assumption $a = d$ are denoted as P^*.

HIP 3795 (*HD 4655 = WDS 00487+1841*) is a quadruple system. The inner AB pair, BU 495, has an orbit with a 143.6 ± 4.0 yr period (Scardia et al. 2000). The CPM component C at 152″ from AB was found by Tokovinin & Lépine (2012), who estimate the probability of it being physical as 0.99. The component C was resolved by R15 into a $0\overset{''}{.}67$ pair Ca,Cb. The PM is too small to determine if the Ca and Cb share common PM, but the low density of background stars and the small separation imply that the pair Ca,Cb is physical.

HIP 4878 (*HD 6152 = WDS 01027+0908*) is a double-lined spectroscopic binary with P = 26.2 days (Griffin & Suchkov 2003). The tertiary companion B at $2\overset{''}{.}8$ did not move substantially in a year since its discovery by R15, but the PM of the main component A is small and the astrometry is not conclusive. B is located below the MS on the CMD, although still within the errors of its photometry. Considering the small field crowding, we count B as likely physical.

HIP 5276 (*HD 6611 = WDS 01075+4116*) is a triple system with the inner 74.1 day spectroscopic pair (Gorynya & Tokovinin 2014) and the tertiary from R15 confirmed as physical by our photometry and astrometry. Our observations demonstrate that the photometry of B given in 2MASS is biased by the proximity of the bright primary, as in many other similar pairs. Their "unusual" colors derived from the 2MASS photometry are thus wrong.

HIP 12925 (*HD 17250 = WDS 02462+0536*) is a quadruple system with a 3-tier hierarchy: a close spectroscopic pair with yet unknown period, the Robo-AO companion D at $1\overset{''}{.}89$, and the CPM companion C at 494″ (Tokovinin & Lépine 2012). Yet another star, HIP 12862, at $0\overset{\circ}{.}9$, also shares the common PM and parallax. The stars are young and belong to the Tucana–Horlogium moving group (Zuckerman et al. 2011). Our photometry places D slightly above the MS. The companion D was independently discovered by Brandt et al. (2014) by high-contrast imaging at Subaru. They measured it on 2012.0 at $252\overset{\circ}{.}9$ and $1\overset{''}{.}893$, in excellent agreement with R15.

HIP 17022 (*HD 22521 = WDS 03390+4232*) is a triple system consisting of an astrometric binary with a period of 3 yr (Goldin & Makarov 2007) and the Robo-AO tertiary B at $1\overset{''}{.}76$. Considering the fast PM(A), the fixed position of AB during 1 year would appear to confirm it as a physical binary. B is located well below the MS, although its photometry has a large uncertainty. If it is a physical component with unusual colors, the system merits further study.

HIP 17129 (*HD 22692 = WDS 03401+3407*) is a known binary, STF 425, which shows apparently a non-Keplerian

[6] http://stellar.dartmouth.edu/models/webtools.html

Table 2
Relative Motion

HIP	Comp.	Δt (year)	$\Delta\mu_{\alpha}^{*}$	$\Delta\ \mu_{\delta}$ (mas yr^{-1})	μ_{α}^{*}	μ_{δ} (mas yr^{-1})	Number 2MASS	Status (P/O)
3795	Ca,Cb	1.2	-4 ± 20	-18 ± 20	-13	-49	0.000	P
4878	AB	1.2	-32 ± 25	-101 ± 23	66	-23	0.004	P?
5276	AB	1.2	56 ± 62	17 ± 36	118	-55	0.047	P
12925	AD	1.2	5 ± 9	28 ± 16	73	-43	0.001	P
17022	AB	1.1	12 ± 24	-11 ± 22	-194	-132	0.008	P?
17217	AC	1.1	48 ± 32	21 ± 48	-49	2	0.059	P?
21443	AB	1.1	29 ± 67	-33 ± 52	-5	20	0.155	P?
25300	AC	14.8	15 ± 7	-20 ± 7	-127	-58	0.087	P
31267	AC	0.2	201 ± 182	766 ± 175	44	31	0.032	?
33355	AC	0.8	-125 ± 64	-149 ± 38	3	-37	0.048	?
86642	AB	1.1	-11 ± 23	7 ± 26	-109	94	0.007	P
96395	AB	14.8	-6 ± 7	22 ± 9	0	-200	0.197	P
101234	AB	1.1	88 ± 21	4 ± 22	-155	-142	0.000	P?
101430	AB	13.8	8 ± 8	6 ± 11	154	140	2.610	P
101430	AE	13.8	-167 ± 10	-140 ± 10	154	140	1.321	O
103455	AB	1.1	50 ± 9	17 ± 10	273	95	0.002	P
104514	AB	1.1	-33 ± 29	43 ± 24	-91	67	0.021	P
108473	AB	13.8	0 ± 7	-4 ± 12	-248	-133	0.122	P
118213	AB	1.2	-4 ± 20	-51 ± 41	76	-134	0.014	P
118225	AB	1.2	-51 ± 49	-13 ± 26	272	-130	0.022	P

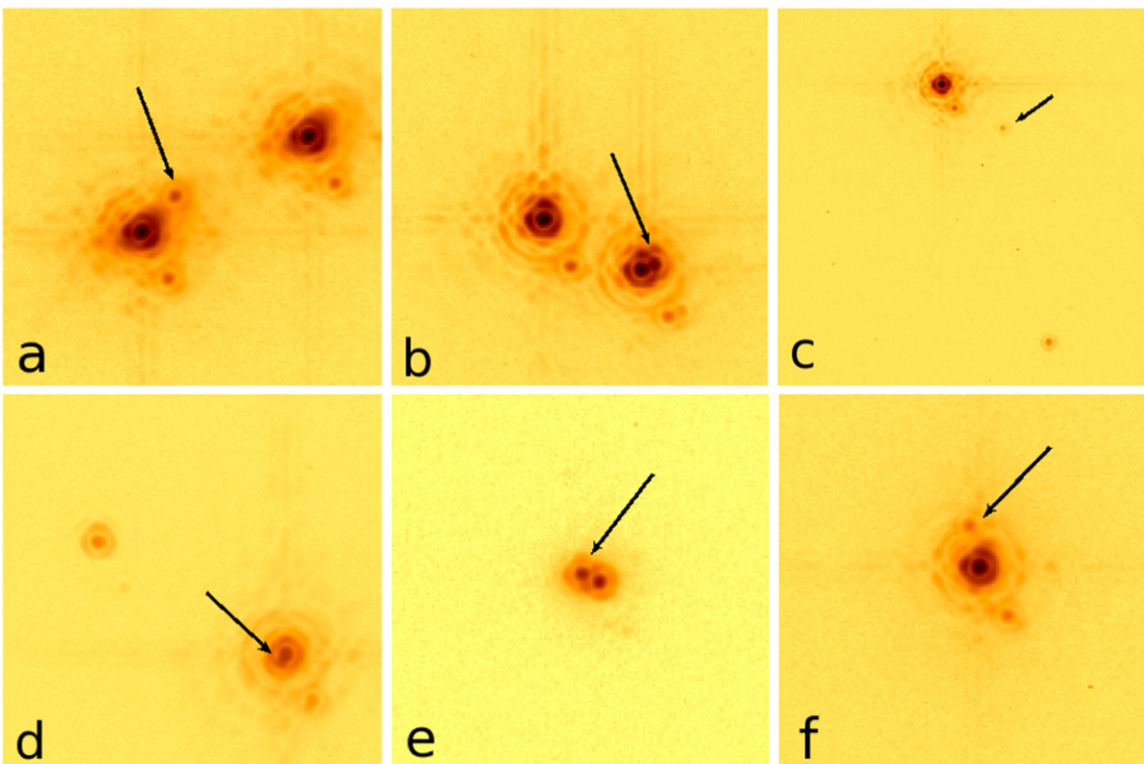

Figure 2. Images of the six new components detected. north is up and east is to the right. The images are: (a) HIP 17129, (b) HIP 25300, (c) HIP 33555, (d) HIP 86642, (e) HIP 101430, (f) HIP 118213. Black arrows point to the locations of the newly imaged companions. The arrows have lengths of one arcsecond. The images were all acquired with the *Ks* filter on 2013 September 28 UT. In each of the images, there is a ghost to the lower right of each star caused by a neutral density filter in the PHARO camera. These are subimages from the actual data frames; the field of view varies and was chosen to best display the binary. The images are all stretched to best display the binary and the PSF structure.

motion. Rica Romero & Zirm (2014) proposed that the motion was caused by an unseen companion and calculated an astrometric orbit for it with $P = 107$ yr, eccentricity 0.61, and photocenter semimajor axis $0.''179$. Our observations were able to resolve the predicted subsystem Aa,Ab. For the time of our observations the orbit predicts a companion position angle of $43.^{\circ}3$, in excellent agreement with the position angle of $44 \pm 1.^{\circ}3$ measured here. The ratio of the predicted displacement to the measured separation of $0.''50$ is $r = 0.32 = q/(1 + q)$. Hence, the mass ratio $q = 0.47$ (the contribution of the light from Ab to the photo-center is neglected). The mass of Aa is estimated at 1.16 $\mathcal{M}_\odot$ from its absolute magnitude, leading to 0.54 $\mathcal{M}_\odot$ for Ab. The absolute magnitude of Ab corresponds to a smaller mass of 0.33 $\mathcal{M}_\odot$. This discrepancy, if confirmed, can be explained by Ab being a close pair of M-dwarfs, as happens in other known multiple systems, e.g., in κ For (Tokovinin 2013). See Figure 2(a) for the discovery image.

HIP 17217 (*HD 22743* = *WDS 03413+4554*) is a known triple system. The inner binary has been known for over a century (Burnham 1894) and its first orbit was computed by R15. R15 also detected a third component C which was confirmed by examination of 2MASS images. The close binary is detectable in our *Ks* images, but the PSFs of the stars are overlapping and we are unable to make a consistent measurement with *fitstars*. We are able to extract the astrometry of the AC pair and consider it as likely physical.

HIP 21443 (*HD 28907* = *WDS 04363+5502*) is triple, consisting of a 2.6 day spectroscopic binary (Gorynya & Tokovinin 2014) and the Robo-AO and 2MASS companion at 5$''$.7. The field is crowded and PM(A) is small. Our photometry places B slightly above the MS. The star is young and active according to Guillout et al. (2009) and we retain B as likely physical.

HIP 25300 (*HD 34839* = *WDS 05247+6323*) is now a 3 tier quadruple system since we resolved the secondary component of the binary AB = STF 677 into a new 0$''$.18 pair Ba,Bb and confirmed that the Robo-AO tertiary C at 7$''$ is physical. We find C to be slightly below the MS, within errors. Although the relative motion of AC is fast, it is not directed away from PM (A) as would be the case for a distant background star; it is produced by the orbital motion of the inner binary AB. The presence of an inner subsystem in the binary AB was suspected previously from its variable RV (Nordström et al. 2004). The estimated masses of Ba and Bb, 0.98 and 0.65 $\mathcal{M}_\odot$ respectively, remove the discrepancy between the mass sum of 3.05 $\mathcal{M}_\odot$ calculated for the AB system from its grade 4 orbit by Hartkopf et al. (2008) and the expected mass sum. Although such discrepancies are not uncommon for low-quality orbits, in this case it serves as an indirect confirmation of Ba,Bb. The estimated period of Ba,Bb is on the order of 20 yr. See Figure 2(b) for the discovery image.

HIP 31267 (*HD 46013* = *WDS 06335+4822*) is another triple where the inner spectroscopic binary with a period of 1.3 yr (D. Latham 2012, private communication) has a tertiary companion discovered with Robo-AO and seen in the archival 2MASS image. This component is located above the MS, but its photometry has large errors. Its status remains indeterminate because the PM(A) is only 0$''$.053 yr^{-1} and we do not have a sufficiently long time base. A wider pair (AB = UC 1450 at 53$''$) was identified as a common PM pair (Hartkopf et al. 2013), however, the colors we find here implies that it is optical. The crowding is moderate. Possibly the preferred motion of background stars accidentally matches the slow PM of A.

HIP 33555 (*HD 50720* = *WDS 06562+4032*) has a slow PM of 0$''$.037 yr^{-1}. The R15 companion at 5$''$.6 is located below the MS and could be optical, despite moderate crowding. We discovered another similarly faint star at 1$''$.9 which was not spotted in the Robo-AO i'-band image. Little can be said about its status. The main target itself is a close spectroscopic binary (D. Latham 2012, private communication) and an X-ray source. See Figure 2(c) for the discovery image.

HIP 86642 (*HD 161163* = *WDS 17422+3804*) is a triple system. The R15 companion at 2$''$.2 is confirmed as physical by its fixed position and its location on the CMD. The main star is a double-lined spectroscopic binary with $P = 6$ yr (D. Latham 2012, private communication) and estimated semimajor axis of 0$''$.1. Our standard algorithm, *fitstars*, produced subpar results on this stars and instead we used the deconvolution technique used in Riddle et al. (2015) to analyze this star. It is resolved here at 0$''$.07. The magnitude difference of Aa,Ab ($\Delta K = 2.43$) matches the spectroscopic mass ratio of 0.52 and corresponds to the Ab mass of 0.60 $\mathcal{M}_\odot$. The orbital motion of Aa,Ab can be followed with AO and speckle interferometry. See Figure 2(d) for the discovery image.

HIP 96395 (*HD 185414* = *WDS 19359+5659*) is triple. Its inner system has a preliminary spectroscopic period of 14 yr and a low amplitude (D. Latham 2012, private communication). Despite the estimated semimajor axis of 0$''$.25, the spectroscopic secondary is too faint for its direct resolution without a high-contrast coronagraph. The 2MASS companion at 10$''$, noted first by Fuhrmann (2004), shares the large PM of A and is located on the MS.

HIP 101234 (*HD 195872* = *WDS 20312+5653*) is an acceleration binary (Makarov & Kaplan 2005) and was first resolved by R15. The position angle in this paper measured on 2013.8367 differs by 27° from the 2012.7592 measurement. That is not the only discrepancy between the two data sets. The photometry with P3K shows large magnitude differences ($\Delta J = 2.5$ and $\Delta K = 2.3$), while Robo-AO detected a binary of equal brightness. This system is not plotted in Figure 1. The separation between the two components is fairly small and in the P3K data, the companion lies on the Airy ring of the primary, which could increase the errors. The primary is a high PM star, the pair AB is most likely a physical binary. Additional observations are necessary to understand this system.

HIP 101430 (*HD 195992* = *WDS 20333+3323*) is a new 2 +2 quadruple system. The outer 17$''$ binary HJ 1535 AB has been known since 1828 (Herschel 1831). If B were a background star, the PM of A, 0$''$.208 yr^{-1}, would have moved it by 38$''$ in 185 yr. The pair AB is therefore undoubtedly physical. The discrepant PM of B reported in the WDS could be caused by the subsystem Ba,Bb discovered here. The main component A has an astrometric subsystem Aa,Ab with $P = 3.9$ yr (Goldin & Makarov 2007), confirmed spectroscopically by D. Latham. The component B was tentatively resolved by Robo-AO, but was thought to be too uncertain to publish in R15. Now Ba,Bb is clearly resolved at 0$''$.17. Its estimated period is on the order of 30 yr. The field is extremely crowded and another faint star E is detected at 12$''$.1 from A by both Robo-AO and PALM-3000. Comparison with 2MASS shows relative motion opposite to PM(A), so AE is optical. See Figure 2(e) for the discovery image.

HIP 103455 (*HD 199598* = *WDS 20577+2624*) is a new 0$''$.6 binary detected by Robo-AO. It was targeted because of its variable velocity (Nordström et al. 2004) and astrometric acceleration (Makarov & Kaplan 2005). The binary is confirmed here, helped by the large PM of the primary. Our photometry places B above the MS. According to Guillout et al. (2009), the target is young, so its companion could indeed be a PMS star. The object was already targeted by Metchev & Hillenbrand (2009) in their survey of young stars, but the binary was not detected. After learning of our discovery, Metchev was able to extract a measurement of the star from the archival data (S. Metchev 2015, private communication).

HIP 104514 (*HD 201639* = *WDS 21102+2045*) has a variable RV (Nordström et al. 2004), so the 3.″3 companion B discovered by Robo-AO makes it a triple system (the estimated period of AB is 2000 yr, too long to cause the RV variation). We found the component B to be on the [Fe/H] = −0.5 isochrone, in agreement with [Fe/H] = −0.54 measured for the star A (Reddy et al. 2003).

HIP 108473 (*HD 208776* = *WDS 21585+0347*) is a single-lined spectroscopic binary with P = 7.18 yr (Nidever et al. 2002) and a large PM of 0.″28 yr^{-1}. The distant component B at 12.″3 is confirmed as physical by 2MASS, Robo-AO, and this work. It is located slightly below the MS, just like HIP 104514B. The object is also metal-deficient relative to the Sun, [Fe/H] = −0.14 (Zielke 1970).

HIP 110574 (*HD 212426* = *WDS 22240+0612*) is a triple system consisting of a close binary Aa,Ab with a separation of 0.″09 detected by R15 and a CPM companion with a separation of 171″. The Aa,Ab system is unresolved in the *Ks* images, but is elongated in the *J* images. We were unable to extract astrometry from the data. The separation has decreased since it was discovered in 2012; Tokovinin et al. (2014) were able to resolve it with visible speckle interferometry at the 4.1 m SOAR telescope on 2013.73 at 41 mas (Tokovinin et al. 2014).

HIP 118213 (*HD 224531* = *WDS 23588+3156*) was previously thought to be a binary, but our observations reveal that it is actually a triple system. The outer component B at 4.″8 was discovered by Robo-AO and confirmed by the 2MASS image and by the new data presented here. It is located near the low end of the MS in Figure 1. The main star with astrometric acceleration (Makarov & Kaplan 2005) is now resolved at 0.″4. This separation corresponds to an orbital period on the order of 100 yr. The new component Ab is too faint for its detection in the i' band with Robo-AO. See Figure 2(f) for the discovery image.

HIP 118225 (*HD 224543* = *WDS 23588+3345*) is a triple system. The inner spectroscopic binary has P = 25.4 days (Latham et al. 2002), the Robo-AO companion at 5″ is seen at a constant position despite PM(A) = 0.″3 yr^{-1}, while its color places it on the MS.

5. SUMMARY

This study shows the power of high-resolution AO imaging for the study of hierarchical multiplicity. We resolved for the first time inner subsystems in six binaries. Four of those (HIP 17129, 86642, 118213, 25300) had previous indications of subsystems from variable RV and/or astrometric acceleration. The AO discovery space overlaps with these alternative techniques, but direct resolution of subsystems allows their characterization in terms of period estimated from separation and mass ratio estimated from photometry. As the orbital periods of these subsystems range from several years to several decades, such characterization by RV or astrometry would necessarily involve a long-term monitoring, which is not available in most cases. The exception is HIP 17129, where a subsystem with P = 107 yr, first resolved here, was inferred from the strange motion of the visual pair observed for almost two centuries.

The new subsystem in the secondary component of HIP 101430 was totally unexpected. This 17″ visual pair known for 185 years is now revealed as a 2+2 quadruple system, where each of the visual components is in turn a close binary. The fainter secondary components of visual binaries generally have much less information on subsystems compared to the brighter primaries (Tokovinin 2014a), and here high-resolution AO imaging makes a large difference.

Our strategy of observing binaries to discover subsystems has been proven successful. The emerging statistics (Law et al. 2010; Tokovinin 2014b) indicates that a third to a half of visual binaries harbor subsystem(s). The simple fact that stellar systems can contain more than just two stars is often forgotten or ignored, for example when comparing PMs of components in wide binaries or calculating their orbits from short arcs while assuming single-star masses. Similarly, RV monitoring of wide binaries in search of exo-planets is incomplete without full characterization of subsystems (Roberts et al. 2015).

This work contributes to the statistical characterization of hierarchical multiplicity in the solar neighborhood. It will help to understand the formation mechanisms that create the panoply of single, binary, and multiple stars, and thus to understand the origin of stars and planets in general.

There is additional work that can be done with these systems. Additional astrometric measurements will show orbital motion confirming that the systems are physically bound. In addition, future astrometric measures can be combined with the RV measurements that have been made on several of the systems and will allow for the computation of the full orbital solution. Though there are strong indications that the newly observed companions are physical, with the exception of HIP 33555, the new companions need to be confirmed with additional observations. Additional observations of HIP 101234 are needed to resolve the discrepancy between the visible and the near-IR differential magnitude. With a period of only six years measured by RV, HIP 86642 Aa,Ab is a prime target for frequent follow up astrometric measurements that can be combined with the double lined spectroscopic orbit.

We thank D. Latham for the insight he provided on a number of these systems. This paper is based on observations obtained at the Hale Telescope, Palomar Observatory. A portion of the research in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA). This research made use of the Washington Double Star Catalog maintained at the U.S. Naval Observatory, the SIMBAD database, operated by the CDS in Strasbourg, France and NASA's Astrophysics Data System. This publication made use of data products from the Two Micron All Sky Survey, which is a joint project of the Universit of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by NASA and the National Science Foundation.

Facility: Hale (PHARO).

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