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SPECKLE INTERFEROMETRY AT SOAR IN 2015*

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ABSTRACT

The results of speckle interferometric observations at the Southern Astrophysical Research Telescope in 2015 are provided, totaling 1303 measurements of 924 resolved binary and multiple stars, and non-resolutions of 260 targets. The separations range from 12 mas to 3$''$37 (median 0$''$17); the maximum measured magnitude difference is 6.7 mag. We resolved 27 pairs for the first time, including 10 as inner or outer subsystems in previously known binaries, e.g., the 50 mas pair in ϵ Cha. Newly resolved pairs are commented upon. We discuss three apparently non-hierarchical systems that have been discovered in this series, arguing that their unusual configurations are the result of projection. The resolved quadruple system HIP 71510 is also studied.

Key words: binaries: general

Supporting material: machine-readable tables

1. INTRODUCTION

Here we report a large set of binary star measurements made at the 4.1 m Southern Astrophysical Research Telescope (SOAR) with the speckle camera, HRCam. This paper continues the series published by Tokovinin et al. (2010b, hereafter TMH10), Tokovinin et al. (2010a), Hartkopf et al. (2012), Tokovinin (2012), Tokovinin et al. (2014), and Tokovinin et al. (2015 hereafter SOAR14). Our primary goals are the characterization of the binary and multiple star population in the solar neighborhood, the improvement of known orbital elements, and the determination of new orbits. Taking advantage of the high angular resolution (~30 mas), we follow close pairs with fast orbital motion and periods of a few years or decades; measurements of other wider and slower binaries are useful for future orbit determination and for checking internal data consistency. A subset of the targets we have observed are drawn from the *Hipparcos* (Perryman & ESA 1997) and Geneva-Copenhagen (Nordström et al. 2004) catalogs. As such, these represent a Southern Hemisphere complement to recent work at Lowell Observatory's Discovery Channel Telescope (Horch et al. 2015).

Orbits of binary stars serve a variety of astrophysical programs. Data on masses are still needed for stars of high and low masses, over a range of metallicities and ages (e.g., pre-main sequence). Accurate parallaxes from *Gaia,* combined with accurate orbits derived from long-term ground-based monitoring, will greatly advance the current census of stellar masses. Orbits of hierarchical multiple systems give insights into their origins and evolution; the same is true for multiple systems containing exoplanets and debris disks. We also provide differential photometry of close pairs.

2. OBSERVATIONS

2.1. Instrument and Observing Method

The observations reported here were obtained with the high-resolution camera (HRCam)—a fast imager designed to work at the 4.1 m SOAR telescope (Tokovinin & Cantarutti 2008). For practical reasons, the camera was mounted on the SOAR Adaptive Module (SAM, Tokovinin et al. 2008). However, the laser guide star of SAM was not used (except in 2015 May); the deformable mirror of SAM was passively flattened and the images are seeing-limited. The SAM module corrects for atmospheric dispersion and helps to calibrate the pixel scale and orientation of HRCam (see SOAR14). The transmission curves of HRCam filters are given in the instrument manual.[6] We mostly used the Strömgren y filter (543/22 nm) and the near-infrared I filter (788/132 nm).

2.2. Observing Runs

The observing time for this program was allocated through NOAO (three nights, programs 15A-0097 and 15B-0009, PI A.T.)and by the Chilean National Time Allocation Committee (three nights in 2015B, program CN2015B-6, PI R.A.M.). All observations were made by A.T., sharing the allocated time between both programs to cover the whole sky and to improve the temporal cadence for pairs with fast motion.

Table 1 lists the observing runs, the calibration parameters (position angle offset θ_0 and pixel scale in mas), and the number of objects covered in each run. The calibration of angle and scale was done with respect to wide pairs with linear motion, as explained in SOAR14. It was revisited and improved by including more calibrators and the 2015 data. The scale is consistent within 0.2%, the calibration of position angle is accurate to 0°1.

In 2015A, the NOAO TAC allocated only two half-nights for this program. Additional observing time was granted by the SOAR director during engineering nights or half-nights. The

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[6] http://www.ctio.noao.edu/soar/sites/default/files/SAM/archive/hrcaminst.pdf

Table 1
Observing Runs

Run	Dates	θ_0 (degree)	Pixel (mas)	$N_{\rm obj}$
1	2015 Feb 7	0.30	15.23	64
2	2015 Mar 2–3	−0.30	15.23	207
3	2015 Apr 1	−0.60	15.23	44
4	2015 May 2–3	−2.74	15.23	195
5	2015 Jun 30	−2.60	15.23	126
6	2015 Jul 16	−2.60	15.23	126
7	2015 Sep 26, 28	−2.68	15.23	323
8	2015 Nov 27–29	−2.84	15.19	425

two nights in May (Run 4) were dedicated to the follow-up of *Kepler-2* exo-host candidates by the Yale University team; measurements of binaries observed when the main targets were out of visibility are published here, while the main results are presented in Schmitt et al. (2016). In this run, the SAM AO system with a UV laser was used to improve the image quality, and hence the magnitude limit on faint *Kepler* targets. The faintest binaries were observed with the laser as well. The gain in sensitivity from using the laser depends on the turbulence profile and other factors, so it is difficult to quantify. A three-night run, Run 7, was allocated for the program of R.A.M. Two nights of this run were lost to bad weather, but an additional engineering half-night was granted to finish the program. The last two-night run, Run 8, in 2015 November, enjoyed a clear sky and good seeing. It was preceded by a half-night of engineering observations taken with the malfunctioning SAM instrument, with strongly aberrated images.

2.3. Data Processing

The procedure for processing data is described in TMH10. As a first step, power spectra and average re-centered images are calculated from the data cubes. The auto-correlation functions (ACFs) are computed from the power spectra. They are used to detect companions and to evaluate the detection limits. The parameters of binary and triple stars are determined by fitting the power spectrum to its model, which is a product of the binary (or triple) star spectrum and the reference spectrum. We used as a reference the azimuthally averaged spectrum of the target itself in the case of binaries wider than 0″.1. For closer pairs, the "synthetic" reference was used (see TMH10).

We added a third option of using observations of single or resolved binary stars as a reference. In the latter case, the signature of the binary is removed from the reference spectrum with the help of the previously fit binary parameters. This works for binaries with $\Delta m \geqslant 1$ mag; otherwise the binary fringes have high contrast and their removal by division increases the noise. The use of reference stars helps in fitting difficult cases such as very faint and/or close companions. Figure 1 shows the elongated power spectrum of the very close pair TOK 197 with a separation of 19.1 mas (under the diffraction limit) observed in 2015.9. The wider 0″.106 pair FIN 363 in the same area of the sky was observed shortly after, with the same y filter and with the same 2 ms exposure. Both data cubes are of excellent quality, showing the speckle signal out to the cutoff frequency. The use of reference stars improves the quality of the fit (a smaller χ^2/N) and assures that any remaining asymmetric distortions of the spectrum, e.g., by telescope vibration, are properly modeled (Figure 2). Observing a large number of binaries with standardized exposure time and filters helped to find references for many targets. We used reference stars when they were available and when they reduced the χ^2/N error metric compared to the standard self-reference technique described in TMH10. The difference between measures of the same object in the y and I filters was generally reduced with reference stars.

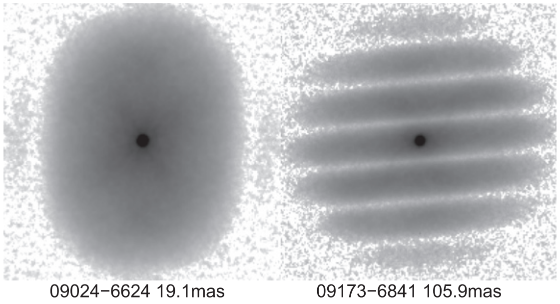

Figure 1. Use of a binary star as a reference. The power spectra on logarithmic scale are displayed for two binaries located in the same part of the sky (y band, 2 ms exposures). The close binary on the left with a separation of 19 mas (below the diffraction limit) is fit better if the binary on the right (106 mas) is used as a reference.

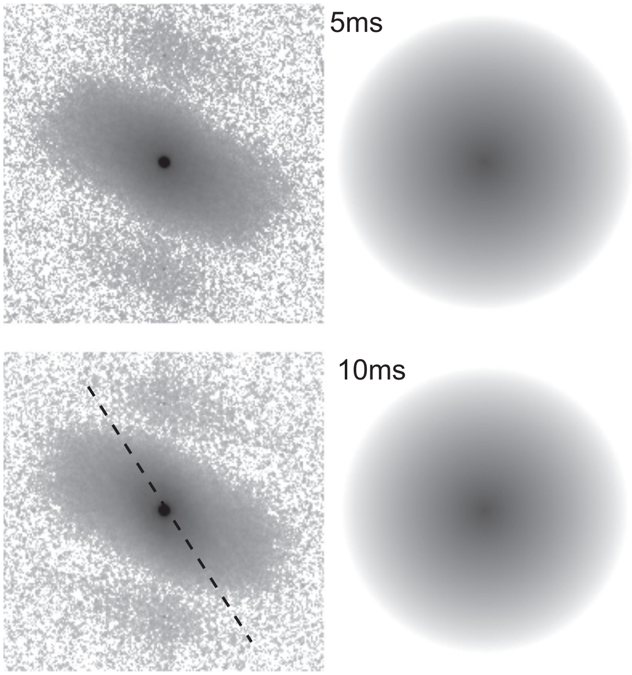

Figure 2. Influence of telescope vibrations on the results. The power spectra of TOK 387 (04386−0920, separation 40 mas) taken in 2015.9 with 5 and 10 ms exposure times are displayed on logarithmic scale, with corresponding "synthetic" references on the right side. The 10 ms data are partially affected by telescope vibration that elongated the central zone of the spectrum in the direction of the dashed line. As a result, the fitted position angle is biased by 6° for the 10 ms data, which were discarded. Use of real reference spectra taken with the same exposure helps to account for vibration-induced asymmetry of the power spectra, avoiding such biases.

Wide binaries resolvable in the re-centered long-exposure images are processed by another code that fits only the magnitude difference Δm, using the binary position from speckle processing. This procedure corrects the bias on Δm caused by speckle anisoplanatism and establishes the correct quadrant (flag * in the data table).

Table 2
Measurements of Double Stars at SOAR (Fragment)

WDS (2000)	Discoverer Designation	Other Name	Epoch +2000	Filt	N	θ (degree)	$\rho\sigma_\theta$ (mas)	ρ ($''$)	$\sigma\rho$ (mas)	Δm (mag)	[O−C]$_\theta$ (degree)	[O−C]$_\rho$ ($''$)	Reference Code[a]
00006−5306	HJ 5437	HIP 50	15.7434	I	2	337.3	0.3	1.4110	1.1	2.7 *			
00008+1659	BAG 18	HIP 68	15.9127	I	2	343.9	0.4	0.7063	0.4	2.7 *			
00024+1047	A 1249 AB	HIP 190	15.9127	I	2	247.2	0.1	0.2808	0.2	0.8 q	179.3	0.046	Zir2003
00036−3106	TOK 686	HIP 290	15.7382	I	3	5.3	1.0	0.1257	1.9	3.2			
			15.9130	I	2	6.5	2.2	0.1160	17.3	3.1 :			
00058−6833	HDS 4	HIP 488	15.9100	I	2	226.0	1.0	0.1920	0.3	1.7 q			
00061+0943	HDS 7	HIP 510	15.7433	I	2	12.3	0.3	0.2515	0.4	0.2			
00071−1551	HDS 11	HIP 584	15.7382	I	2	261.9	1.6	0.4093	0.7	2.6 q			
00090−5400	HDO 181	HIP 730	15.7434	I	2	20.9	0.2	0.3655	0.6	2.1 q	−4.5	−0.014	Ary2002b

Note.
[a] References to VB6 are provided at http://ad.usno.navy.mil/wds/orb6/wdsref.txt.

(This table is available in its entirety in machine-readable form.)

We also calculated shift-and-add (SAA or "lucky") images, centered on the brightest pixel in each frame and weighted proportionally to the intensity of that pixel. All frames without rejection were co-added. Binary companions, except the closest and the faintest ones, are detectable in these SAA images, helping to identify the correct quadrant. Such cases are marked by the flag q in the data table. Quadrants of the remaining binary stars are guessed based on prior data or orbits, not measured directly.

3. RESULTS

3.1. Data Tables

The data tables have almost the same format as in the previous papers of this series. They are available in full only electronically. Table 2 lists 1303 measures of 924 resolved binary stars and subsystems, including 27 newly resolved pairs. The columns of Table 2 contain (1) the WDS (Mason et al. 2001) designation, (2) the "discoverer designation" as adopted in the WDS, (3) an alternative name, mostly from the *Hipparcos* catalog, (4) Besselian epoch of observation, (5) filter, (6) number of averaged individual data cubes, (7, 8) position angle θ in degrees and internal measurement error in tangential direction $\rho\sigma_\theta$ in mas, (9, 10) separation ρ in arcseconds and its internal error σ_ρ in mas, and (11) magnitude difference Δm. An asterisk follows if Δm and the true quadrant are determined from the resolved long-exposure image; a colon indicates that the data are noisy and Δm is likely overestimated (see TMH10 for details); the flag "q" means the quadrant is determined from the SAA image. Note that in cases of multiple stars, the positions and photometry refer to the pairings between individual stars, not the photocenters of subsystems.

For stars with known orbital elements, columns (12–14) of Table 2 list the residuals to the ephemeris position and code of reference to the orbit adopted in the Sixth Catalog of Orbits of Visual Binary Stars (Hartkopf et al. 2001, hereafter VB6).[7]

Table 3 contains the data on 260 unresolved stars, some of which are listed as binaries in the WDS or resolved here in other filters. Columns (1) through (6) are the same as in Table 2, although Column (2) also includes other names for objects without discoverer designations. For stars that do not have entries in the WDS, fictitious WDS-style codes based on the J2000 position are listed in Column (1). Column (8) is the estimated resolution limit equal to the diffraction radius λ/D. Columns (8, 9) give the 5σ detection limits Δm_5 at $0.''15$ and $1''$ separations determined by the procedure described in TMH10. When two or more data cubes are processed, the largest Δm value is listed. The last column features colons that mark noisy data that are mostly associated with faint stars. In such cases, the quoted Δm might be too large (optimistic); however, the knowledge that these stars were observed and no companions were found is still useful for statistics.

3.2. Newly Resolved Pairs

Table 4 lists 27 newly resolved pairs. Its format is similar to that of Table 2. For some multiple systems, we used existing discover codes and simply added new component designations. The last two columns of Table 4 contain the spectral type (as given in SIMBAD or estimated from absolute magnitude) and the *Hipparcos* parallax (van Leeuwen 2007, hereafter HIP2). Fragments of ACFs of newly resolved triple systems are shown in Figure 3. We comment on these objects below. The following abbreviations are used: PM—proper motion, CPM—common proper motion, RV—radial velocity, SB1 and SB2—single- and double-lined spectroscopic binaries. Orbital periods are estimated from projected separation as $P^* = (\rho/p)^{3/2}M^{-1/2}$, where ρ is the angular separation, p is parallax, M is the mass sum, and P^* is the period in years. Data from the spectroscopic Geneva-Copenhagen Survey (GCS; Nordström et al. 2004) are used for some targets.

00036-3106. HIP 290 is a binary detected by its astrometric acceleration (Makarov & Kaplan 2005) and variable RV (GCS). The separation implies an orbital period of $P^* = 17$ year.

00164-2235. The faint tertiary companion to HIP 1306 at $1.''1$ was first resolved in direct and coronagraphic adaptive-optics (AO) images by Boccaletti et al. (2004), although this is not reflected in the WDS. They quote a separation of $1.''075$ and a magnitude difference of 3.5 mag at 2.12 μm between A and C, but do not list the position angle. Looking at their Figure 9, it is similar to 254° measured here, while we find $\Delta I = 4.9$ mag.

01077-1919. HIP 5291 (HD 6720) was observed because the GCS detected double lines (SB2). However, it is likely that the new $0.''6$ companion with $\Delta I = 4.8$ mag is a tertiary.

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[7] See http://ad.usno.navy.mil/wds/orb6/wdsref.html

Table 3
Unresolved Stars (Fragment)

WDS (2000) α, δ (J2000)	Discoverer Designation or Other Name	*Hipparcos* or Other Name	Epoch +2000	Filter	N	$\rho_{\min}$ (arcsec)	5σ Detection Limit		Δm Flag
							Δm (0.″15) (mag)	Δm (1″) (mag)	
00012−0005	TOK 359	HIP 93	15.7433	I	3	0.040	3.95	5.07	…
00036−3106	TOK 686	HIP 290	15.9130	y	2	0.028	4.87	6.41	…
00039−2824	HIP 305	HIP 305	15.7382	I	2	0.040	4.35	5.26	…
00052−6251	HIP 425	HIP 425	15.7434	I	2	0.040	4.14	4.99	…
00138+0812	HIP 1103	HIP 1103	15.7433	I	2	0.040	4.03	5.34	…
00194−4007	HIP 1552	HIP 1552	15.9130	I	2	0.040	3.97	6.37	…
00219−2300	HJ 1957 A	HIP 1732	15.7382	I	2	0.040	4.17	5.64	…
00221−2643	HIP 1746	HIP 1746	15.9130	I	2	0.040	4.04	5.51	…

(This table is available in its entirety in machine-readable form.)

Table 4
Newly Resolved Pairs

WDS (2000)	Discoverer Designation	Other Name	Epoch +2000	Filt	θ (degree)	ρ (″)	Δm (mag)	Sp. Type	$\pi_{\rm HIP2}$ (mas)
00036−3106	TOK 686	HIP 290	15.7382	I	5.3	0.1257	3.2	F9V	15.4
00164−2235	HDS 36 Aa,C	HIP 1306	15.7382	I	254.5	1.1000	4.9	G3V	13.1
01077−1919	TOK 687	HIP 5291	15.7382	I	41.8	0.6077	4.8	G8V	11.4
01380+0946	TOK 688	HIP 7604	15.7383	I	13.4	0.0559	2.2	F5	5.1
03322−3134	TOK 691	HIP 16481	15.7435	I	312.6	0.1656	3.9	F0V	3.9
06467+0822	HDS 940 BC	HIP 32475	15.9081	y	2.4	0.0828	0.3	F0IV	14.6
10111−7227	HDS 1468 BC	HIP 49879	15.1688	I	241.2	0.0631	0.3	F3V	7.0
10172−7252	HEI 494 A,Ca	HIP 50381	15.2502	I	302.1	0.6793	2.9	A8V	5.2
10172−7252	HEI 494 Ca,Cb	HIP 50381	15.2502	I	153.1	0.1020	0.8	A8V	5.2
10269−5340	TOK 693 Aa,Ab	HIP 51144	15.1714	I	322.6	0.3464	2.1	F6V	4.8
11106−3234	I 213 AC	HIP 54611	15.1686	I	156.9	0.1687	3.1	F5IV	6.8
11596−7813	HJ 4486 Aa,Ab	ϵ Cha	15.2502	y	57.3	0.0512	0.2	B9V	9.0
16004−5107	TOK 694	HD 143055	15.1689	I	219.5	0.0246	1.5 :	F0V	…
18040+0150	TOK 695	HIP 88481	15.3358	y	26.5	0.0608	1.8 q	G5	29.0
19064−1154	RST 4028 Ba,Bb	HIP 93827	15.7374	I	78.2	0.2520	0.0	M0V	26.3
19512−7248	TOK 697 Aa,Ab	HIP 97690	15.3359	y	30.9	0.0212	1.0 :	F6V	11.5
19563−3137	TOK 698	HIP 98108	15.5410	I	58.9	0.0801	1.1 q	G3V	17.0
20048+0109	TOK 699	HIP 98878	15.4973	I	317.7	0.1571	2.5 q	G5	26.1
20286−0426	TOK 700	HIP 100998	15.4972	I	222.4	0.1081	0.6 q	F8	15.3
20574−5905	TOK 701 Ba,Bb	HIP 103438B	15.5411	I	258.9	0.1496	0.7 q	G5V?	18.6
22139−2216	TOK 702	HIP 109753	15.7379	I	39.2	1.7792	4.9 *	G5V	12.0
22300+0426	STF 2912 Ba,Bb	HIP 111062	15.9127	y	268.4	0.0599	0.8	F8+A4	19.3
22308−2410	HDS 3192 Aa,Ab	HIP 111133	15.5413	I	149.8	0.0545	0.4 q	K1III	3.5
22441+0644	TOK 703	HIP 112240	15.4974	I	54.2	0.0380	0.8	F5	17.1
23224−4636	CPO 637 Aa,Ab	HIP 115386	15.9128	I	48.8	1.1456	5.2 *	G5V	15.3
23228+2034	TOK 704 Ba,Bb	HIP 115417B	15.7379	I	181.2	0.7470	2.0 q	K0V?	26.8
23296−4001	HDS 3346 AC	HIP 115957	15.9128	I	315.9	0.3494	4.3	G6V	6.8

(This table is available in machine-readable form.)

01380+0946. HIP 7604 (HD 10016) is listed in the GCS as an SB with a mass ratio of 0.960 ± 0.010 and [Fe/H] of -0.20. Apparently the SB is resolved here and shows a rapid motion. It was observed by lunar occultations but not resolved (Richichi et al. 2006), and also unresolved by speckle interferometry with the WIYN telescope (Horch et al. 2011).

03322-3134. HIP 16481 (HD 22054) is an SB2 with a period of 10.1 days, equal-mass components, and a small eccentricity of 0.13 (Nordström et al. 1997). Obviously, the 0.″17 interferometric companion found here cannot correspond to the spectroscopic one, so the system is triple.

06467+0822. HIP 32475 (HD 49015) is a variable star of γ Dor type V839 Mon, an X-ray source, and a 0.″3 visual binary HDS 940. It was observed by speckle interferometry at the WIYN telescope several times (e.g., Horch et al. 2008). Re-examination of the WIYN data by one of the authors of this paper (E.H.) shows doubling of the secondary in 2005, 2007, and 2012, confirming its resolution here. The separation of BC implies an orbital period of $P^* \sim 10$ year; further observational and archival data will soon lead to the determination of its orbit.

10111-7227. The secondary component of HDS 1468 is resolved into the close 63 mas pair BC. Its projected separation implies $P^* \sim 20$ year. Indeed, the pair BC is in rapid retrograde motion, turning by 16° during 2015.

10172-7252. A new component C to HEI 494 AB is discovered at a separation of 0.″67. This component itself is also a 0.″07 binary Ca,Cb. The resolution is confirmed by re-

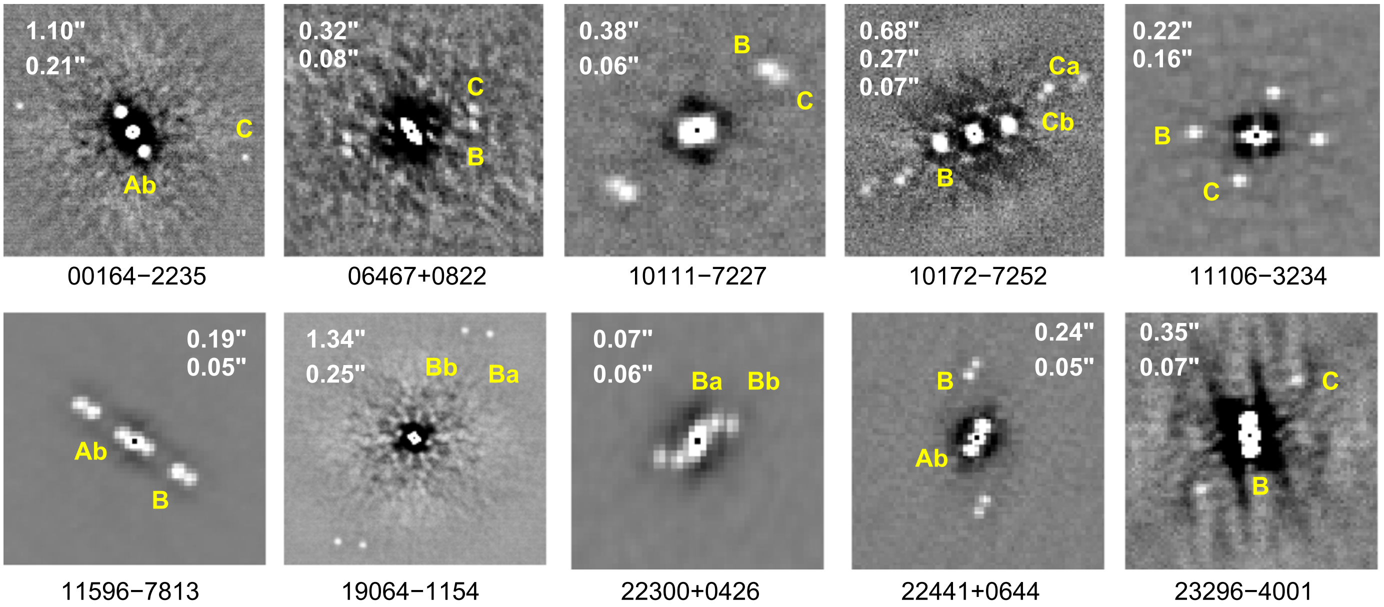

Figure 3. Fragments of ACFs of newly resolved triple systems (north up, east left, arbitrary scale). Peaks in the ACFs are labeled by component designations. Angular separations in the wide and close pairs are listed in the images.

observation in the following runs. The relative position and magnitude difference of Ca,Cb are measured only crudely. If C is physical to AB (the object has a low galactic latitude, so the sky is crowded), this is a new 2 + 2 quadruple.

10269-5340. HIP 51144 is an SB2 according to the GCS. It was resolved for the first time at 0.″37 in Run 2 and confirmed in Runs 3 and 9. The projected separation implies $P^* = 430$ year, so the new companion is not the one causing double lines. The system is likely triple. Using *Hipparcos* photometry, Koen & Eyer (2002) found periodic variability with $P = 1.33$ days and an amplitude of 0.03 mag.

11106-3234. The pair I 213, known as a binary since 1879, unexpectedly turned out to be a triple system in a nearly equilateral triangular configuration, with two components, B and C, having similar brightness (both are about 3 mag fainter than A). It was confirmed on the following night, showing that this is not a transient. This system is discussed in the next subsection.

11596-7813. This is the B9V star ε Chamaeleontis (HR 4583), the most massive member of the association bearing its name. Known as a binary HJ 4486 AB since 1835, it turns out to be a triple system composed of three similar stars. It is surprising that the inner 50 mas pair Aa,Ab was not discovered earlier in high-resolution surveys of the ε Cha association. The separation implies $P^* \sim 7$ year, so rapid motion of Aa,Ab is expected. The fringes of Aa,Ab have unit contrast. Processed as a binary, the subsystem Aa,Ab has a magnitude difference of $\Delta y = \Delta I = 0.2 \pm 0.05$ mag, while the triple-star fit gives a slightly larger Δm. The components Aa and B are also equal and our photometry agrees with the $\Delta Hp_{\rm AB} = 0.69$ mag measured by *Hipparcos*. Note the linear configuration of this triple in Figure 3. The outer pair AB was at (179°, 1.″6) in 1835 and has now closed down to (235°, 0.″19). Its nearly radial motion suggests a highly inclined or eccentric orbit. Study of this interesting triple system can give some clues for understanding the peculiarity of this association, which lacks both low-mass stars and wide binaries according to Becker et al. (2013).

16004-5107. HD 143055 (F0V) was observed on request from K. Helminiak. The elongated power spectrum indicates tentative resolution, confirmed in another run. However, the measures are of low accuracy.

18040+0150. According to D. Latham (2012, private communication), HIP 88481=HD 165045 is an SB2 with a period of 1.6 year and a mass ratio of 0.6; its low mass function suggests a face-on orbit. The expected semi-major axis is 46 mas, in agreement with the measured separations and the fast motion of 110° yr^{-1} observed over three runs.

19064-1154. The faint secondary of HIP 93827 (HD 177758) is resolved into a 0.″25 pair of equal stars. Their estimated masses are 0.5 $\mathcal{M}_\odot$; the period of Ba,Bb is $P^* \sim 30$ year. This is a solar-type triple system within 67 pc.

19512-7248. HIP 97690 = HD 186502 (F6V) is an SB2 according to the GCS. Goldin & Makarov (2007) computed astrometric orbit with $P = 2.877$ year, implying a semi-major axis of 28 mas. While the separations measured in three runs match the expected axis, the angles disagree with the astrometric orbit; the pair moves very fast.

19563-3137. HIP 98108 = HD 188432 (G3V) has double lines (GCS) and astrometric acceleration. The 80 mas separation implies a short period $P^* \sim 7$ year. The star was not resolved in a survey of astrometric binaries at Gemini-South (Tokovinin et al. 2012).

20048+0109. HIP 98878 = HD 190412 is a spectroscopic triple with periods of 251 days and 7.8 yr (D. Latham 2012, private communication). The outer period corresponds to the axis of 0.″10, and the tertiary was resolved at 0.″16. Astrometric acceleration was also detected. The star is on the exoplanet search program at the Keck telescope.

20286-0426. The GCS suspected that HIP 100988 has a variable RV. Its resolution at 0.″10 implies an orbital period $P^* \sim 10$ yr.

20574-5905. The 4.″6 pair COO 241 AB (HIP 103438) belongs to the 67 pc sample. We observed both components separately and resolved the secondary into a new 0.″15 pair Ba, Bb with an estimated period of $P^* \sim 20$ year. The outer pair has a much longer period of $\sim$40 kyr. Desidera et al. (2006) detected an RV difference of 2 km s^{-1} between A and B, which can partly be caused by the motion of Ba,Bb. The pair Ba,Bb is more massive than the single star A; it is located above the main sequence, as expected for a binary.

22139-2216. HIP 109753 is an SB2 in the GCS. The faint companion at 1.″8 found here could be a tertiary if it is not optical.

22300+0426. This bright star 37 Peg (HR 8566) is a well-known visual binary STF 2912 with an orbital period of 125 yr. Despite the extensive literature, which includes speckle coverage, the binarity of the secondary component has never been suspected. Here it is resolved into a close pair which, projected on the primary, forms an apparently non-hierarchical configuration. The system is further discussed in Section 3.4.

22308-2410. The bright star HIP 111133 (K1III) was resolved by *Hipparcos* at 0.″2 and has never been confirmed since. Its observation at SOAR shows a change in angle by 6°, while the primary component is a new 53 mas pair Aa,Ab. The fringes of Aa, Ab are of high contrast; processing it as a binary gives $\Delta y = \Delta I = 0.2 \pm 0.05$ mag, while the triple-star fit gives a slightly larger $\Delta m \sim 0.4$ mag. The period of Aa,Ab is $P^* \sim 40$ yr. Considering their similar colors, both Aa and Ab are giants at a similar evolutionary stage.

22441+0644. The acceleration binary HIP 112240 (F5) is resolved at 38 mas, implying a period of $P^* \sim 2$ year. The RV variability was detected by the GCS. It was not resolved in the following run and tentatively resolved again in 2015.7 and 2015.9. All measures are derived by fitting the elongated power spectrum (no second fringe is detected), so they are of questionable accuracy.

23224-4636. HIP 115386 belongs to the 67 pc sample. It has a CPM companion at 38.″5. Both components were observed at SOAR. While B was unresolved, we found a new faint pair AC at 1.″14. The sky is not crowded, so AC is likely physical.

23228+2034. HIP 115417B was resolved at the Gemini-North telescope in 2015 (E.H. and A.T., in preparation). It is confirmed here, while the A-component is unresolved. The subsystem Ba,Bb causes a "wobble" with a period of $\sim$115 yr in the observed motion of the 5.″9 pair AB.

23296-4001. The known close binary HIP 115987 was observed in the y and I bands. The new faint component C at 0.″35 is seen only in I.

3.3. Comments on Other Pairs

02418-5300. The close pair CD−53° 544 was first resolved by Elliott et al. (2015) in a survey of young stars (see also 02305−4342 = ELP 1 and 08138−0738 = ELP 2 measured here). However, no measures of this pair were published in the discovery paper, so the designation TOK 690 Aa,Ab is adopted here.

04074-4255. The primary of HDS 522 has spectral type K0III: the secondary is bluer, which explains its non-resolution in the I filter.

13401-6033. New measurement confirms that the 0.″9 pair BC is physical, despite the crowdedness of the sky in this area.

3.4. Apparently Non-hierarchical Triples

The discovery of the triple system HIP 54611 (WDS J11106−3234, I 213) in a nearly equilateral triangular configuration (Figure 3) raises the question of its dynamical stability. Small N-body systems with comparable separations decay during a few crossing times, leaving binaries and ejected single stars (e.g., Harrington 1972). Non-hierarchical triples are thus expected to exist only at very young ages. The T Tau triple HD 34700 found by Sterzik et al. (2005) could be such a case. On the other hand, dynamically stable triples can appear in non-hierarchical configurations in projection on the sky. Triple systems with small period ratios are more likely to be found in non-hierarchical projected configurations, as HIP 54611. Here we discuss this and two other such triple systems observed with HRCam.

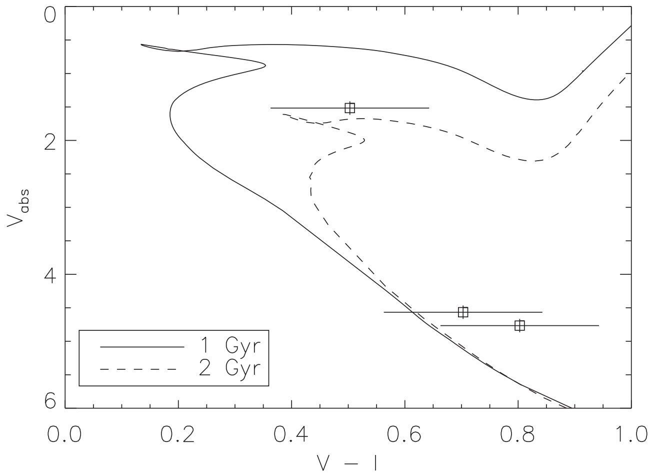

Figure 4. Position of the three components of HIP 54611 on the Dartmouth isochrones (Dotter et al. 2008) for solar metallicity and ages of 1 and 2 Gyr.

HIP 54611. The spectral type of HIP 54611 is F5IV/V, its parallax is 6.80 ± 0.6 mas. The combined photometry in the HIP2 catalog is $V = 7.24$ and $I_C = 6.71$ mag. Assuming that our differential photometry in the y and I filters also applies to the V and I_C bands, we compute individual magnitudes of A,B, C as $V = (7.35, 10.4, 10.6)$ and $I_C = (6.85, 9.7, 9.8)$ mag, with 0.1 mag estimated errors. All stars appear to be above the main sequence (Figure 4), suggesting an age of A around 2 Gyr. It is unlikely that these stars are still evolving toward the main sequence.

Most likely, the subsystem BC is projected close to the main component A. Our photometry gives $V_{\rm BC} - V_{\rm A} = 2.39$ mag, while *Hipparcos* measures $\Delta Hp = 2.24 \pm 0.117$ mag, taking BC as an unresolved star. The relative position of A,BC measured by *Hipparcos* also matches this assumption. In 1879 A,BC was at (135°, 1.″0), in 1991.25 at (118°, 0.″311), and in 2015.17 at (115.°6, 0.″156). The angular separation follows the linear trend $\rho_{\rm A,BC}(t) \approx 0.257 - 0.0072\,(t - 2000)$. The speed of relative motion of 7.2 mas yr^{-1} corresponds to 1.06 au yr^{-1}.

With projected separations of 1″ and 0.″2 for A,BC and BC, respectively, and the masses of 1.6, 1, and 1 solar for A, B, and C, estimated from the isochrones, we obtain the statistical periods P^* of 940 yr for A,BC and 110 yr for BC. The 1″ separation and speed of A,BC also correspond to a circular orbit with a 1 kyr period. The outer orbit cannot have a large eccentricity, as the estimated period ratio is on the order of 10, rather close to the critical ratio of 4.7 for a circular outer orbit.

HIP 85216. Another "triangular" star HIP 85216 (WDS J17248−5913, I 385 AB and WSI 87 AD) was discovered with HRCam in 2008. All three components are of similar brightness, spectral type A0V, HIP2 parallax 3.15 ± 0.96 mas. The pair AB has been known since 1900. Figure 5

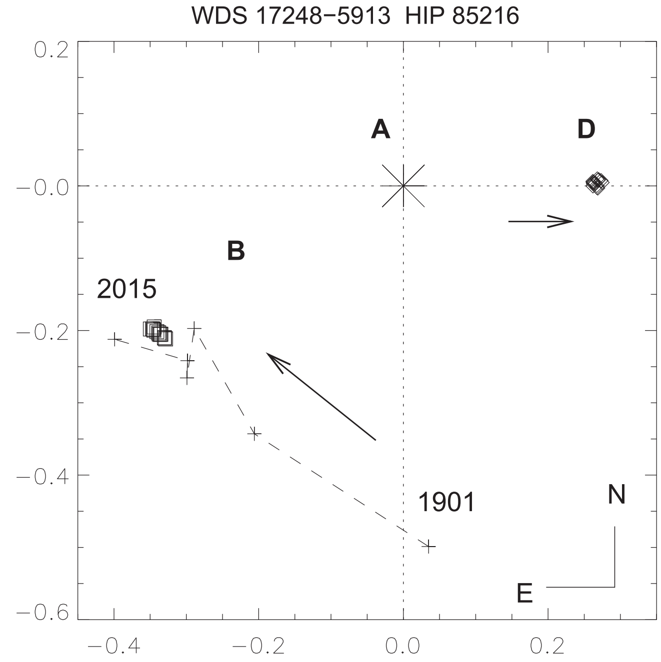

Figure 5. Relative motion of apparently non-hierarchical system HIP 85216 (I 385 AB and WSI 87 AD). Crosses mark measures of AD,B; squares are accurate speckle measurements of A,B and A,D. The scale is in arcseconds, and arrows show the direction of motion.

shows that B has moved by 65° relative to A since its discovery. Accurate speckle measurements over seven years match the general trend. The motion of AB can be represented by a tentative orbit with $P = 1244$ yr, $T_0 = 2374$, $e = 0.35$, $a = 0.''95$, $\Omega = 237°$, $\omega = 237°$, $i = 108.^\circ5$. This orbit corresponds to a reasonable mass sum of $5.2\,\mathcal{M}_\odot$.

Over seven years, component D moved much less than B. Its position angle is constant, the separation increases at a rate of 1.5 mas yr^{-1}. Extrapolating back in time, the separation of AD was $0.''1$ in 1900 when the AB was discovered. With an estimated $P^* = 200$ year for AD we expect a motion of 9 mas yr^{-1}, 6 times faster than actually observed.

There are two possibilities. Either the orbit of AD has a very high eccentricity and the system is presently seen near its apastron, or the actual period of AD is much longer than the period of AB and we see it close to A only in projection. As the orbital speed is proportional to $P^{-1/3}$, the observed slow motion of AD suggests a period of ~40 kyr rather than 200 yr as implied by the projected separation. In such case the semi-major axis of AB,D would be on the order of $7''$. However, there is another physical component C at $17''$, threatening the dynamical stability of AB,D if it had a $7''$ axis. The odds that a $7''$ binary is seen at $0.''27$ are about 10^{-3}, so statistically it is more likely that AD is located inside AB, rather than outside. Considering the long periods, the issue will be hard to settle with further observations in the coming decades.

Whatever the true organization of the HIP 85216 multiple system actually is, it is clear that the apparent non-hierarchical configuration could be a result of projection. However, the true ratio of separations or periods is not very large, so the system as a whole could be close to the limit of dynamical stability.

HIP 111062. Figure 6 illustrates yet another apparently non-hierarchical configuration found unexpectedly in the otherwise "boring" classical binary STF 2912 (HIP 111062, WDS J22300+0426). Its first observation with HRCam in 2008 shows a simple binary, with a minor deviation from the orbit of Soderhjelm (1999), $P = 125$ year, $e = 0.5$, $i = 89°$. The orbit is seen nearly edge-on. The system was observed again in 2015.5 after passing through the conjunction. The ACF looked somewhat strange, but it was processed as a binary and showed a reasonable agreement with the orbit. However, in 2015.9 the secondary was clearly resolved into a pair of nearly equal stars Ba and Bb. We plotted in Figure 6 the average position of Ba and Bb for this epoch.

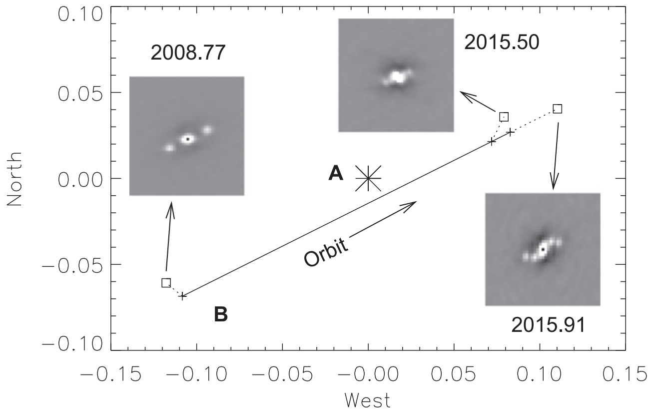

Figure 6. Motion of STF 2912 and its triple nature. The ACFs at three epochs are displayed in the inserts. The line and the crosses depict the orbit of Soderhjelm (1999); the squares denote the measured positions of B (the mean of Ba and Bb in 2015.9).

The magnitude differences in the y band measured in 2015.9 are $\Delta m_{\mathrm{A,Ba}} = 2.2$ and $\Delta m_{\mathrm{Ba,Bb}} = 0.8$ mag. The combined light of Ba and Bb then leads to $\Delta m_{\mathrm{AB}} = 1.78$ mag, in good agreement with $\Delta m = 1.89$ mag measured by *Hipparcos*. This suggests that the stars Ba and Bb form a close pair that is identified with the "historic" companion B. The projected separation of the pair Ba,Bb in 2015.9 was 60 mas, or 3.1 au. Assuming the mass sum of Ba+Bb to be $2\,\mathcal{M}_\odot$, we estimate its period as $P^* \sim 3.4$ year. Rapid motion of this subsystem is thus expected. Considering that the orbit of AB is seen edge-on and that the pair Ba,Bb is oriented roughly along its plane, we suggest that the two sub-systems might actually be almost coplanar. Further observations will quickly prove if this is indeed the case. Trilling et al. (2007) found IR excess in this and other binary systems, suggesting the presence of dust. They noted that the main star, A, is evolved above the main sequence.

The growing family of multiple systems with "weak" hierarchy (i.e., small ratio of outer to inner periods) is interesting from a dynamical perspective, as the motions in the outer and inner orbits are coupled and their representation by two Keplerian orbits is inaccurate. The first two systems discussed here move slowly on the human timescale. On the other hand, STF 2912 and other tight multiples among nearby dwarfs discovered at SOAR are much faster, and their monitoring will yield interesting results in the not so distant future.

3.5. The Quadruple System ADS 9323 (HIP 71510)

Observations at SOAR revealed HIP 71510 (HD 128563, WDS J14375+0217, ADS 9323) as a resolved quadruple system. Its HIP2 parallax is 13.37 ± 1.1 mas, the PM is $(-38, -70)$ mas yr^{-1}. It is an X-ray source RX J14375+0216. The outer pair AB (A 2227) was discovered by R. Aitken in

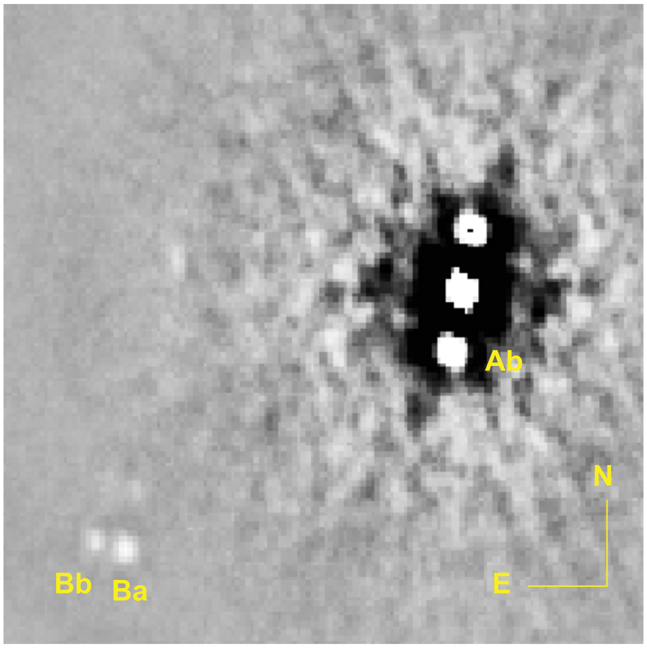

Figure 7. Fragment of the ACF of HIP 71510 in the y filter recorded on 2009.26. Very faint peaks corresponding to the correlation of Ba and Bb with Ab are barely seen. The faint details at 85° and 265° are filter ghosts.

1910 at (138°, 2″.1). The secondary component B is 4 mag fainter than A, so the binary was not resolved by *Hipparcos*. Presently AB closed down to (124°.5, 1″.25). The speed of the relative motion of AB in 100 years is about 8 mas yr^{-1}, matching its expected orbital motion and an order of magnitude less than the PM of A. The system AB is thus definitely physical. Its estimated orbital period is on the order of 500 yr.

The inner subsystem Aa,Ab known as CHR 42, was resolved in 1984. Its first orbit by Hartkopf & Mason (2010) was recently updated in SOAR14: orbital period 21.54 year, axis 0″.143, eccentricity 0.844. The HIP2 parallax and orbital elements give the mass sum of 2.64 $\mathcal{M}_\odot$.

The system was first observed at SOAR in 2009.26. The secondary component B was resolved into a 0″.1 pair (Figure 7). However, the data processing tools do not provide for fitting four stars, and the binarity of B was not mentioned explicitly in TMH10. The speckle observations in 2014 and 2015 were made mostly for the purpose of following the orbit of Aa,Ab, which closed down. The subsystem Ba,Bb was noted, but still not measured. In 2015.46 the Aa,Ab pair closed down almost below the diffraction limit, and the data were processed as a triple system (A,Ba,Bb) for the first time.

The Ba,Bb pair was measured approximately with an accuracy of ~0.5 pixel (8 mas). The results are listed in Table 5. The pair is in a slow retrograde motion. Its period as estimated from separation is on the order of 20 yr. The motion of AB is also retrograde, while Aa,Ab is in direct motion.

SIMBAD does not provide the *BV RI* photometry of the star, but it is found in Metanomsky et al. (1998). The differential photometry is furnished by the SOAR speckle. The results are assembled in Table 6. The faintness of Ba and Bb and approximate data processing make its speckle photometry quite uncertain, while the magnitudes of Aa and Ab are established securely.

Table 5
Crude Measurements of HIP 71510 Ba,Bb

Date (year)	Filt.	θ (degree)	ρ (″)	Δm (mag)
2009.6290	y	77.0	0.100	1.02
2014.3030	y	73.3	0.113	0.62
2015.1716	y	72.6	0.103	0.64
2015.4966	I	70.1	0.097	0.45
2015.4967	y	69.8	0.099	0.66

Table 6
Photometry of HIP 71510

Component Combination	V or y (mag)	I_C (mag)	J (mag)	K_s (mag)
A+B	6.45	5.83	5.45	5.11
A−Aa	2.10	1.96	…	…
Ba−Aa	5.06	4.4*	…	…
Bb−Ba	0.64	0.5*	…	…

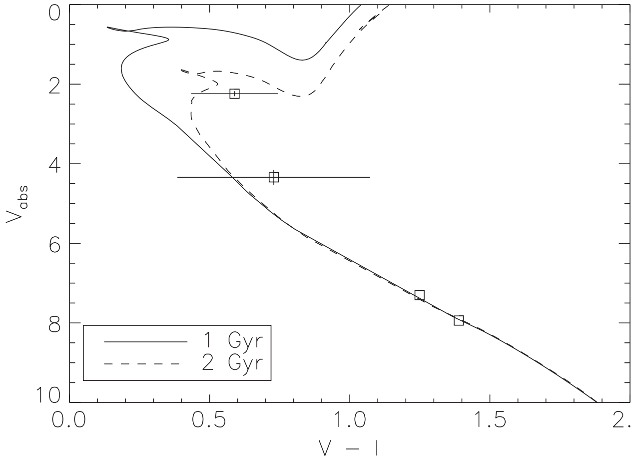

Figure 8. Location of the four components of HIP 71510 on the Dartmouth isochrones (Dotter et al. 2008) for solar metallicity. The error bars are shown only for Aa and Ab.

The combined light of the system is dominated by component Aa. It is classified as F9V, which matches the combined color. However, the absolute V magnitude of Aa is 2.2 mag, about 2 mag brighter than a normal F9V dwarf. We cannot question the HIP2 parallax (it gives a reasonable mass sum of Aa,Ab), so Aa is definitely above the main sequence. Treating the system as a single star, Casagrande et al. (2011) derived $T_e = 6343$ K, mass 1.75 $\mathcal{M}_\odot$, and age ~1.5 Gyr.

Figure 8 shows the position of the components of ADS 9323 on the Dartmouth isochrones (Dotter et al. 2008). The differential magnitudes of Ba and Bb in the I_C band were adjusted by trial and error so that they fall on the main sequence (numbers with asterisks in Table 6); they do not contradict the crude speckle photometry. The system is slightly older than 2 Gyr. The mass of Aa from isochrones is about 1.62 $\mathcal{M}_\odot$, the mass of Ab is 1.22 $\mathcal{M}_\odot$, and the mass sum of Aa+Ab is then 2.82 $\mathcal{M}_\odot$. It matches the mass derived from the orbit, 2.64 ± 0.65 $\mathcal{M}_\odot$, within its error (which is mostly due to the parallax uncertainty). The masses of Ba and Bb are estimated as 0.74 and 0.68 $\mathcal{M}_\odot$.

4. SUMMARY

The extremely productive speckle interferometry program at SOAR gives a unique look into the structure and dynamics of multiple systems in the solar neighborhood. We focus on close pairs resolved by our predecessors, by *Hipparcos*, and in the previous speckle runs at SOAR. The inventory of new pairs is enlarged by the 27 first resolutions that are reported here.

The 1303 measurements made at SOAR in 2015 are used for the calculation and improvement of orbits, both by our team (e.g., the 198 orbits in SOAR2014, where some measurements reported here were already used) and by other authors, e.g., WDS J22504−1744 (Docobo et al. 2015). Slow motion of some binaries means that this material will be used for a long time. Its value will increase further when accurate parallaxes from *Gaia* become available. The short duration of this space mission makes long-term monitoring of orbital motion from the ground, such as that provided here, its essential complement.

Although measurement of stellar masses is still needed in many areas, orbital elements give a wealth of other information. For example, their statistics are useful for testing theories of binary formation. This is particularly true for systems with more than two bodies, e.g., hierarchical multiples and binaries hosting planets. Period ratios, eccentricities, and angles between orbital planes allow dynamical analysis of these complex astrophysical systems enabling us to gain insights into their origins and evolution. Here we characterize motions in three apparently non-hierarchical triple systems and one quadruple discovered with HRCam.

High angular resolution and deep dynamic range allow us to discover new components in previously known binaries, sometimes quite unexpectedly (Figure 3). Here we established that ϵ Cha consists of three nearly equal stars, not two as believed before. This is the most massive member of a young association in the solar vicinity. The period of the inner pair discovered here is only a few years, so monitoring it further will soon provide the masses of B9V pre-main-sequence stars in a triple system.

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Facility: SOAR.

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