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KNOW THE STAR, KNOW THE PLANET. II. SPECKLE INTERFEROMETRY OF EXOPLANET HOST STARS

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ABSTRACT

A study of the host stars to exoplanets is important for understanding their environment. To that end, we report new speckle observations of a sample of exoplanet host primaries. The bright exoplanet host HD 8673 (= HIP 6702) is revealed to have a companion, although at this time we cannot definitively establish the companion as physical or optical. The observing lists for planet searches and for these observations have for the most part been pre-screened for known duplicity, so the detected binary fraction is lower than what would otherwise be expected. Therefore, a large number of double stars were observed contemporaneously for verification and quality control purposes, to ensure that the lack of detection of companions for exoplanet hosts was valid. In these additional observations, 10 pairs are resolved for the first time and 60 pairs are confirmed. These observations were obtained with the USNO speckle camera on the NOAO 4 m telescopes at both KPNO and CTIO from 2001 to 2010.

Key words: binaries: general – binaries: visual – stars: individual (HD 8673) – techniques: interferometric

Online-only material: color figure, machine-readable and VO tables

1. INTRODUCTION

As discussed in Paper 1 of this series (Roberts et al. 2011) a study of the host stars to exoplanets is essential if we wish to understand the environment in which those planets formed. Further, the star's luminosity, distance, mass, and other characteristics are fundamentally related to the determination of the planet's mass and size. Determining these parameters directly for the host star as opposed to using a template of the canonical stellar class and type will produce more accurate and precise planetary determinations. As part of this effort we herein report new speckle observations of a large sample of exoplanet host primaries.

Binaries affect the formation and stability of planetary systems, as their long-term relationship must be hierarchical. Generally speaking, based on the precepts of Harrington (1981) if the ratio of semimajor axes is 4:1 or greater, an exoplanet in a stellar binary is dynamically stable. Dynamically permitted systems include the more commonly detected configuration of planet(s) orbiting one stellar component of a sufficiently wide-orbit binary in a hierarchical arrangement, and the harder-to-detect circumbinary configuration of planet(s) in a wide orbit around a close stellar binary (see Raghavan et al. 2006, especially Section 6.1). That said, Raghavan et al. (2010) in their statistics updating and improving upon Duquennoy & Mayor (1991) find that while the frequency of single stars is the same, the number of companions has increased through instrumental and technique enhancements. Due to the presence of stellar companions, one might imagine the environment of binary stars to be a rich one for substellar companions. However, dynamical effects should eject companions not found in hierarchical orbits. In any event, as conducive as this environment might be to companions, this is not reflected in the list of known planet hosts, however. This is due entirely to selection effects; because of the complexities of disentangling stellar companions from small planetary signatures, the observing lists for planet searches have for the most part been pre-screened for known duplicity, so the detected binary fraction is lower than what would be expected.

In addition to binary stars that are gravitationally bound, there are optical doubles which are merely chance alignments of unrelated stars. Although they do not contribute dynamically to the system, close optical pairs do contribute light to the system, which should be accounted for in system analysis. While photometric analysis of binary systems can infer "third" light in the system, radial velocities or periodic variation in other astrometric parameters (for example, the *Hipparcos* acceleration solutions), would not give evidence of these companions. Optical pairs would best be found by direct imaging or interferometric analysis.

2. SPECKLE OBSERVATIONS

All of these observations were obtained as part of other observing projects, for example, analysis of white, red, and subdwarfs (Jao et al. 2009), G dwarfs (Section 5.3.6 of Raghavan et al. 2010), or massive stars (Mason et al. 2009), some of which are still in developmental and/or data collection stages. Unpublished observations of exoplanet host stars were extracted from these data and are presented here. The instrument used for these speckle observations was the USNO speckle interferometer, described most recently in Mason et al. (2009).

Speckle interferometry is a single filled-aperture interferometric technique where the "speckles" of a pair of nearby stars, induced by atmospheric turbulence, constructively interfere. Reduced by simple autocorrelation methods, in the resulting image

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Table 1
New Interferometric Double

Coordinates α,δ (2000)	WDS or α,δ (2000)	Discoverer Designation	HIP	BY 2000.0+	θ (deg)	ρ ($''$)	Δm (mag)	Sep (AU)
012608.78 + 343446.9	01262 + 3435	WSI 96	6702	1.0193	257.3	0.087		3.3
				7.6049	78.3	0.109	2.3	4.2

the binary or double star geometry is the predominant structure when compared with the other uncorrelated pairings. It is capable of resolving pairs to the resolution limit of the telescope in question up to the size of the observation field (typically, $\sim 1''.5$), as long as the pairs have magnitude differences of less than about three.

Calibration of the KPNO data was accomplished through the use of a double-slit mask placed over the "stove pipe" of the 4 m telescope during observations of a bright known-single star (as described in Hartkopf et al. 2000). This application of the Young's double-slit experiment allowed determination of scale and position angle zero points without relying on binaries themselves to determine calibration parameters. Multiple observations through the slit mask (during five separate KPNO runs from 2001 to 2008) yielded mean errors of $0^\circ.11$ in the position angle zero point and 0.165% in the scale error. These "internal errors" are undoubtedly underestimates of the true errors for these observations, because these calibration tests were made on stars that were brighter and nearer the zenith than science stars. Total errors are likely three to five times larger than these internal errors.

Because the slit-mask option is not available on the CTIO 4 m telescope, we calibrated the Southern Hemisphere data using observations of numerous well-observed wide equatorial binaries obtained at both the KPNO and CTIO telescopes. Published orbital elements for these pairs were updated as needed, using the recent KPNO and published measures, then predicted ρ and θ values from those orbits deemed of sufficiently high quality were used to determine the CTIO scale and position angle zero points. The calibration errors for these southern observations were (not surprisingly) considerably higher than those achieved using the slit mask. Mean errors for five CTIO runs from 2001 to 2010 (as well as a 2001 KPNO run lacking slit mask data) were $0^\circ.67$ in position angle and 1.44% in scale. These errors are likely overestimated, because we have assumed that the calibration binaries have perfect orbits, and any offsets are incorporated into the errors.

3. RESULTS

Following generation of the directed vector autocorrelation (Bagnuolo et al. 1992), the "DVA" is background subtracted through boxcar subtraction and the sharp central peak, which corresponds to the zeroth-order speckles correlating with themselves, is clipped. Companions in the resulting DVA are then readily apparent as peaks several sigma above the background.

Of the 118 exoplanet hosts we observed only one, HIP 6702 showed signs of a companion and is discussed in Section 3.1 and listed in Table 1. The null results are listed in Table 2, a list of single star detections. In the table, Column 1 gives the *Hipparcos* number, Column 2 the HD Catalog number, Column 3 lists other common designations, Column 4 is the epoch of observation, and Column 5 identifies the telescope (C = Cerro Tololo 4 m, K = Kitt Peak 4 m). For all of these observations no companion was detected within the ranges $\Delta m_V < 3$, and $0''.03 < \rho < 1''.5$.

Table 1 lists the observations for this new detection. Column 1 gives the precise position of the system, Column 2 is the Washington Double Star Catalog (hereafter WDS; Mason et al. 2001) identifier, and Column 3 lists the discovery designation, here the WSI (Washington Speckle Interferometry) number. Column 4 gives the *Hipparcos* number of the primary as a cross-reference. Column 5 gives the epoch of observation, and Columns 6 and 7 provide the relative astrometry. Column 8 lists a crude estimate of the magnitude difference of the pair in the V band (the listed number is paired with the more reliable observation). This estimate is probably only good to ± 0.5 mag. Column 9 provides the separation in astronomical units, based on the *Hipparcos* parallax and this angular separation assuming a face-on orbit.

The resulting multiplicity fraction is extremely low, but artificially so. Observation of known binaries is a prime goal of the USNO speckle program and some of these pairs had been previously published (e.g., HD 28305 in Mason et al. 2009). Others which were known but whose motions were not especially compelling (e.g., HD 50583 in Mason et al. 2011) were observed with our 26 inch refractor in Washington and those which do have a compelling individual story to tell unrelated to exoplanets are in preparation (C. D. Farrington et al. 2012, in preparation). A simplistic multiplicity determination of this limited result (= 1/118) is therefore not a meaningful number.

3.1. New Double Star: HIP 6702

Of all the exoplanet hosts which have been serendipitously observed, all were unknown as close visual doubles and only one of the host stars, HIP 6702 (= HD 8673), appeared double in directed vector autocorrelations on both times it was observed. The classification of HIP 6702 as an exoplanet is based upon Hartmann et al. (2010) who, using iodine-cell radial velocity measurements, detected a companion with an $M \sin i$ of 14.2 M_j with a period of 1634 $\pm$ 17 days and an eccentricity of 0.723 $\pm$ 0.016. The relative astrometric measures of this resolved pair are provided in Table 1. Given the small number of measures presented in Table 2, the pair, while a visual double star, is not necessarily a binary system. Verification of physicality for the new companion to HIP 6702 can be accomplished several ways, among them color–magnitude, proper motion, and/or kinematic analysis. The speckle interferometry observable of relative position establishing kinematic–physical (i.e., Keplerian) motion requires at least three measures. So, while close proximity can be a powerful argument for physicality, it is by no means definitive (cf. ι Ori; Section 5.1 of Mason et al. 2009). Nevertheless, even a companion which is only nearby in the angular sense should be considered in any detailed analysis of the star, as it will contribute to the photometric signature of the examined target. Such is the case for HIP 6702, which was recently reported as a sub-stellar companion (Hartmann et al. 2010).

Among the possible interpretations of the new speckle companion two stand out: first, the companion is a non-physically associated line-of-sight companion and second, it is the companion detected in Hartmann et al. (2010).

Table 2
Stars with No Companion Detected

HIP	HD	Common Name	BY 2000.0+	Telescope
522	142	. . .	1.5621	C
1292	1237	GJ 3021	1.5674	C
1499	1461	. . .	1.5701	C
3391	4113	. . .	1.5647	C
3479	4208	. . .	1.5647	C
3497	4308	. . .	1.5648	C
5054	6434	. . .	1.5622	C
5529	7199	. . .	1.5675	C
5806	7449	. . .	1.5675	C
6379	7924	. . .	1.0218	K
7513	9826	υ And	1.0220	K
7599	10180	. . .	1.5702	C
7978	10647	. . .	1.5702	C
8159	10697	. . .	1.0300	K
9683	12661	. . .	1.0165	K
10138	13445	GJ 86	1.5676	C
10626	13931	. . .	1.0219	K
12186	16417	. . .	1.5676	C
12189	16246	30 Ari	1.0304	K
12653	17051	ι Hor	1.5676	C
14954	19994	. . .	1.0820	C
15323	20367	. . .	1.0193	K
15527	20782	. . .	1.0820	C
16537	22049	ϵ Eri	10.0652	C
17096	23079	. . .	1.0738	C
20723	28185	. . .	1.0764	C
24681	34445	. . .	1.0306	K
25110	33564	. . .	1.0222	K
26381	37124	. . .	1.0307	K
26394	39091	. . .	1.0740	C
26394	39091	. . .	6.1937	C
26664	37605	. . .	1.0306	K
27887	40307	. . .	1.0740	C
27887	40307	. . .	6.1937	C
28767	40979	. . .	1.0224	K
29804	43848	. . .	1.0793	C
30034	44627	AB Pic	1.0740	C
30579	45364	. . .	1.0794	C
30860	45350	. . .	1.0198	K
30905	45652	. . .	1.0308	K
31246	46375	. . .	1.0767	C
31540	47186	. . .	1.0794	C
32916	49674	. . .	1.0224	K
32970	50499	. . .	1.0794	C
33212	50554	. . .	1.0279	K
33719	52265	. . .	1.0823	C
36795	60532	. . .	1.0795	C
37826	62509	. . .	1.0199	K
38041	63765	. . .	1.0742	C
38558	65216	. . .	1.0742	C
40693	69830	. . .	6.1911	C
40952	70642	. . .	1.0743	C
43587	75732	55 Cnc	1.0200	K
46076	81040	. . .	1.0770	C
47007	82943	. . .	1.0797	C
47202	83443	. . .	1.0744	C
48235	85390	. . .	1.0744	C
48739	86226	. . .	1.0797	C
49699	87883	. . .	1.0202	K
50473	89307	. . .	1.0310	K
50921	90156	. . .	6.1912	C
52521	93083	. . .	1.0799	C
53721	95128	47 UMa	1.0202	K
54906	97658	. . .	1.0203	K
57172	101930	. . .	1.0746	C
57291	102117	. . .	1.0746	C
57370	102195	. . .	1.0311	K
57443	102365	. . .	6.1915	C
57443	102365	. . .	10.0659	C
57931	103197	. . .	1.0746	C
58451	104067	. . .	6.1915	C
59610	106252	. . .	1.0312	K
64295	114386	. . .	1.0827	C
64426	114762	. . .	1.0232	K
64457	114783	. . .	5.1915	C
64459	114729	. . .	1.0775	C
64459	114729	. . .	1.0802	C
64924	115617	61 Vir	6.1890	C
64924	115617	61 Vir	8.4500	K
64924	115617	61 Vir	10.0688	C
65721	117176	70 Vir	1.0232	K
65721	117176	70 Vir	6.1916	C
67275	120136	. . .	1.0314	K
67275	120136	τ Boo	6.1916	C
71395	128311	. . .	1.5664	C
71395	128311	. . .	6.1916	C
72339	130322	. . .	1.0829	C
74500	134987	. . .	1.0830	C
74500	134987	. . .	1.5611	C
77740	141937	. . .	1.5666	C
78459	143761	ρ CrB	8.4503	K
79242	142022A	. . .	1.5667	C
79248	145675	14 Her	1.4986	K
80250	147018	. . .	1.5667	C
80337	147513	. . .	6.1919	C
83389	154345	. . .	1.4960	K
83949	155358	. . .	1.4961	K
86796	160691	μ Ara	1.5667	C
87330	162020	. . .	1.5642	C
88348	164922	. . .	8.4506	K
90004	168746	. . .	1.5614	C
90485	169830	. . .	1.5614	C
91085	171238	. . .	1.5614	C
94075	178911B	. . .	1.4990	K
94645	179949	. . .	1.5614	C
96901	186427	16 Cyg	1.4991	K
97336	187123	. . .	1.4990	K
97546	187085	. . .	1.5670	C
98505	189733	. . .	8.4614	K
98767	190360	. . .	8.4563	K
99711	192263	. . .	5.8680	K
99825	192310	GJ 785	1.5616	C
101806	196050	. . .	1.5615	C
101966	196885	. . .	8.4481	K
104903	202206	. . .	1.5618	C
106006	204313	. . .	1.5618	C
106353	204941	. . .	1.5618	C
108375	208487	. . .	1.5672	C
108859	209458	. . .	8.4615	K
109378	210277	. . .	1.5645	C
111143	213240	. . .	1.5618	C
112441	215497	. . .	1.5646	C
113137	216437	. . .	1.5647	C
113238	216770	. . .	1.5646	C
113357	217014	51 Peg	7.5883	K
113357	217014	51 Peg	8.4617	K
116727	222404	γ Cep	1.0218	K
116727	222404	γ Cep	1.4993	K
116906	222582	. . .	1.5674	C

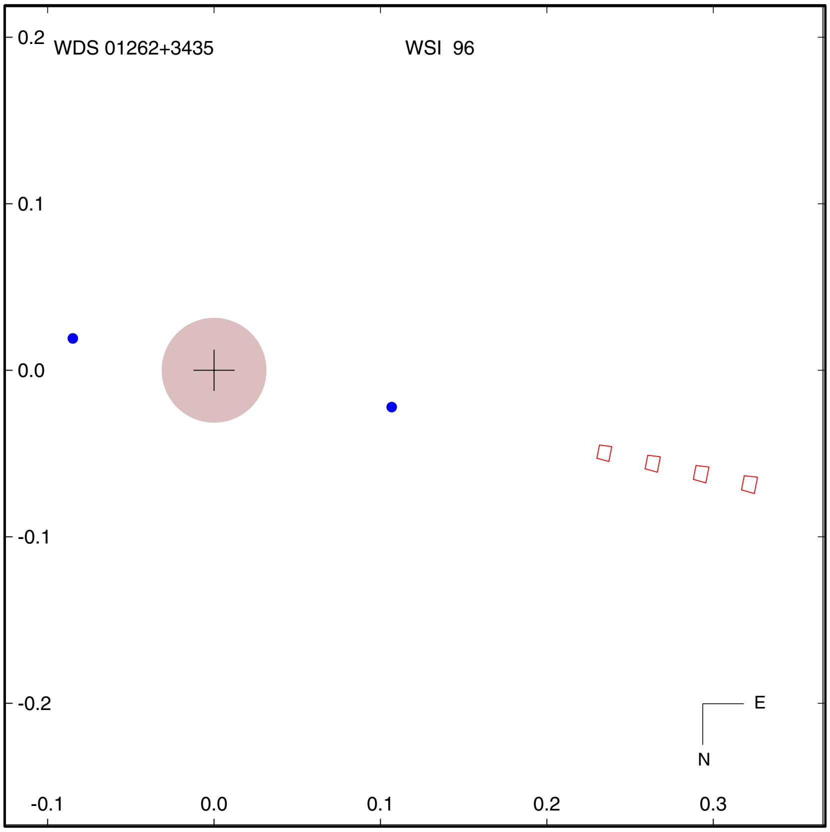

Figure 1. "Motion characterization" system plot for HIP 6702 (= WSI 96) with small filled circles indicating the 2001 and 2007 speckle measures from Table 1. Scales are in arcseconds, and in each figure the large shaded circle represents the *V*-band resolution limit of a 4 m telescope. The four small error boxes in each figure indicate the predicted location of that pair's secondary in 2012.0, 2013.0, 2014.0, and 2015.0, assuming the motion is linear and all speckle measures are characterized by errors of $\Delta\theta = 1^{\circ}\!.0$, $\Delta\rho/\rho = 1.0\%$. Finding the double within a box appropriate to the observation date would be a strong indication that the relative motion of the pair is linear (that is, just motion from an unrelated field star due to proper motion differences). The **H** indicates where the companion would have been at 1991.25, at the *Hipparcos* epoch.

(A color version of this figure is available in the online journal.)

3.1.1. Physical Companion?

Hipparcos has produced many types of double star solutions. The ones which can be most easily compared to other detection techniques and the most common are those where the relative parameters (ρ, θ) are presented. The speckle interferometry measures presented in Table 1 are both near the *Hipparcos* "C" code double star solution cutoff ($0''\!.082$ for HDS 446 = HIP 27151). The other *Hipparcos* double star solutions may not be applicable here. Some depend upon a priori orbital information (O code), system dynamics in the plane of the sky (G code), variability (V code), or unknown parameters (X and/or S code). In any event, the lack of *Hipparcos* detection is a condition which is neither necessary nor sufficient to establish that the Hartmann et al. (2010) companion is not stellar.

However, if the two Table 1 measures represent relative measures of the Hartmann et al. (2010) pair, the inclination must be extremely low. Assuming a near zero inclination the mean separation of $0''\!.098$ would approximate the angular semi-major axis (a$''$ = $0''\!.098 \pm 0''\!.011$). Given this, the *Hipparcos* parallax of 26.14 ± 0.79 mas and the Hartmann et al. period of 1634 ± 17 days, a mass sum of 2.63 ± 0.92 $M_{\odot}$ is obtained, which is not unreasonable for two similar F dwarf stars, although the error is quite large, primarily due to the uncertainty in a''. The length of time between the two speckle observations represents 1.47 times the Hartmann et al. period. The two measures of angular position represent $(0.497$ or $0.503) + n$ revolutions of the system (depending on the direction of rotation), which is very similar to the Hartmann et al. period when $n = 1$.

Given the estimated dynamic range ($\Delta m_{\rm V} = 2.3 \pm 0.5$) and assuming the fainter limit and spectral type of the primary this would make the secondary close to a K2V. Using the canonical mass of a K2V in $M \sin i = 14.2 M_j$ gives an inclination of $1^{\circ}\!.02$. Using this inclination with $a \sin i$ from Hartmann et al. (2010) gives a semi-major axis of $0''\!.168$ which is consistent with the Table 1 results.

3.1.2. Optical Companion?

Since the interferometric companion to HIP 6702 has been observed so few times, establishing the companion as optical or physical is not possible. The proper motion of the primary is $0''\!.25$ yr^{-1} ($\alpha = 0''\!.236$ yr^{-1}, $\delta = -0''\!.085$ yr^{-1}). From the relative positions in Table 1, the proper motion of the companion would be an even higher at $0''\!.276$ yr^{-1}. If linear motion is assumed and reasonable errors are applied it is possible to determine where the companion would be at some date in the future. In Figure 1, this determination is performed assuming errors slightly larger than nominal for the two speckle interferometry measures: $\Delta\theta = 1^{\circ}\!.0$, $\Delta\rho/\rho = 1.0\%$. The predicted position for 2012 through 2015 are plotted as error boxes. Again, assuming linear motion from the two speckle points, a separation of $0''\!.37$ and a position angle of 255° is determined for 1991.25, which

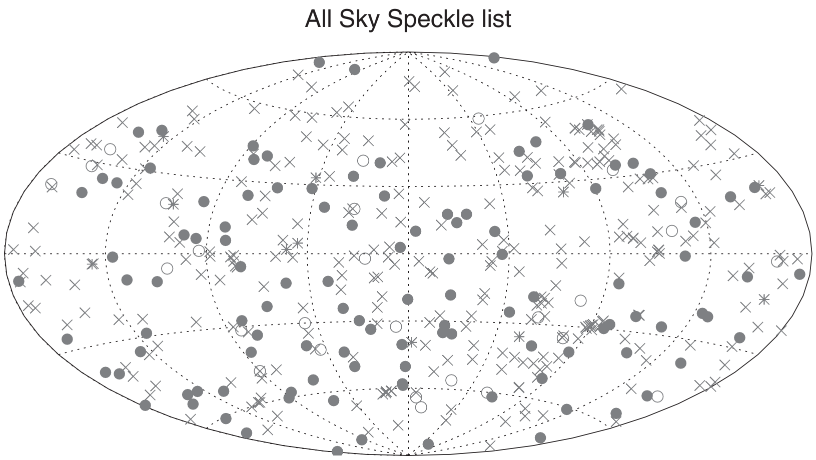

Figure 2. Aitoff projection of all 444 targets. Filled circles ($N = 114$) are those listed in Table 2. Open circles ($N = 27$) are those observed by CHARA or USNO with an ICCD and reduced with the DVA method. Asterisks ($N = 11$) are those observed by other interferometry groups, and an "X" ($N = 292$) are those which have yet to be observed. A valid speckle measure is only counted if it was obtained on a 4 m class telescope.

would be well within the capabilities of the *Hipparcos* satellite (Perryman & ESA 1997).

4. FUTURE OBSERVING

Due to the relatively even distribution of targets not yet observed by speckle interferometry, one observing run in each semester and each hemisphere will be necessary in order to observe all remaining exoplanet host stars. However, the target list for each of the four runs will be slight—less than one hundred stars each. With an approximately equal number of quality control and equatorial scale calibration pairs, each observing run could easily be completed in two to three nights. Priority would obviously be given to targets not observed before. Those observed by other speckle interferometric groups would be next in priority so that they all have a common reduction algorithm. Figure 2 is an Aitoff plot of targets from the list of known exoplanet host stars taken from the NStED[7] database and gives their observation status.

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Table 3
Other Pairs Measured

WDS or α,δ (2000)	Discovery Designation	HIP	BY 2000.0+	θ (deg)	ρ ($''$)	Note
00024 + 1047	A 1249 AB	190	7.5994	74.8	0.135	
00026 − 0829	A 428	210	7.6019	344.5	0.174	
00055 − 1835	RST 3340	...	1.5701	287.4	0.303	
00095 + 1907	COU 247	768	7.5992	259.1	0.294	
00117 + 6145	TDS 1338	...	7.6074	111.2	0.527	1
00167 + 3629	STT 4	1336	7.6021	99.7	0.232	
00174 + 0853	A 1803 AB	1392	7.6019	307.2	0.145	
00182 + 7257	A 803	1461	7.6021	307.9	0.262	
00233 + 5132	TDS 1431	...	7.6074	102.5	0.227	1
00271 − 0753	A 431	2143	1.5021	184.5	0.139	
			1.5647	189.0:	0.139:	
			7.6019	13.3	0.201	

Notes.
[1] Confirming observation.
[2] Two measurements are averaged to give this mean position.
[3] Calibration system.
[4] Previously known as RST3558a.
[5] Confirmed with HRCam on SOAR 4.2 m, CTIO 4 m (Tokovinin et al. 2010).
[6] Three measurements are averaged to give this mean position.
[7] First measure of newly resolved pair. Primary is HD 341480.
[8] Confirming observation or more likely a new component.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

APPENDIX

ADDITIONAL MEASURES OF KNOWN PAIRS

Due to the high incidence of single stars among the exoplanet hosts, a substantial number of double stars were observed contemporaneously with the exoplanet host observations to ensure that the observing conditions and detection capabilities given above were met. Additional measures of known or suspected doubles were made as time permitted. Table 3 lists 550 mean

[7] http://nsted.ipac.caltech.edu/cgi-bin/bgServices/nph-bgExec, extracted 2011 April 12.

positions for 485 known systems. Column 1 is the WDS identification (arcminute coordinate), Column 2 lists the discovery designation, and Column 3 provides the *Hipparcos* number. Column 4 gives the epoch of observation, and Columns 5 and 6 provide the relative astrometry. Column 7 contains the notes for these systems. Also found in the table are 10 pairs resolved for the first time and 60 pairs which are here confirmed; estimated magnitude differences for the new pairs (when available) are listed in the notes column.

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