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THE HIGH ANGULAR RESOLUTION MULTIPLICITY OF MASSIVE STARS

Brian D. Mason[1,4], William I. Hartkopf[1,4], Douglas R. Gies[2], Todd J. Henry[2], and John W. Helsel[3]
[1] U. S. Naval Observatory, 3450 Massachusetts Avenue, NW, Washington, DC 20392-5420, USA; bdm@usno.navy.mil, wih@usno.navy.mil
[2] Center for High Angular Resolution Astronomy, Department of Physics and Astronomy, Georgia State University, P.O. Box 4106, Atlanta, GA 30302-4106, USA; gies@chara.gsu.edu, thenry@chara.gsu.edu
[3] Department of Physics, Furman University, 3300 Poinsett Hwy., Greenville, SC 29613, USA; john.helsel@furman.edu
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ABSTRACT

We present the results of a speckle interferometric survey of Galactic massive stars that complements and expands upon a similar survey made over a decade ago. The speckle observations were made with the Kitt Peak National Observatory and Cerro Tololo Inter-American Observatory 4 m telescopes and USNO speckle camera, and they are sensitive to the detection of binaries in the angular separation regime between $0\farcs03$ and $5''$ with relatively bright companions ($\Delta V < 3$). We report on the discovery of companions to 14 OB stars. In total we resolved companions of 41 of 385 O-stars (11%), 4 of 37 Wolf-Rayet stars (11%), and 89 of 139 B-stars (64%; an enriched visual binary sample that we selected for future orbital determinations). We made a statistical analysis of the binary frequency among the subsample that are listed in the Galactic O Star Catalog by compiling published data on other visual companions detected through adaptive optics studies and/or noted in the Washington Double Star Catalog and by collecting published information on radial velocities and spectroscopic binaries. We find that the binary frequency is much higher among O-stars in clusters and associations compared to the numbers for field and runaway O-stars, consistent with predictions for the ejection processes for runaway stars. We present a first orbit for the O-star δ Orionis; a linear solution of the close, apparently optical, companion of the O-star ι Orionis; and an improved orbit of the Be star δ Scorpii. Finally, we list astrometric data for another 249 resolved and 221 unresolved targets that are lower mass stars that we observed for various other science programs.

Key words: binaries: general – binaries: visual – stars: early-type – stars: individual (iota Ori, delta Ori, delta Sco) – techniques: interferometric

Online-only material: machine-readable and VO tables

1. INTRODUCTION

Massive stars appear to love company. There is growing evidence that the incidence of binary and multiple stars among the massive O- and B-type stars is much larger than that for solar-type stars (see Zinnecker & Yorke 2007 and references therein). This difference in multiplicity properties may ultimately reflect differences in the star-formation process between massive and low-mass stars. For example, while low-mass stars may lose angular momentum by magnetic- and disk-related processes, it may be that these are ineffective in massive star formation because of the very short timescale of formation. Instead, the initial angular momentum of the natal cloud may end up (through a variety of processes) in the orbital angular momentum of binaries among the more massive stars (Bate et al. 2002; Zinnecker & Yorke 2007; Gies 2007).

The observational evidence for the high incidence of binaries among the massive stars comes from spectroscopic investigations of short-period systems and high angular resolution measurements of longer period (and wide) binaries. We made one of the most comprehensive surveys of the bright, Galactic O-type stars in a speckle interferometric study made in 1994 with the NOAO 4 m telescopes in both the northern and southern hemispheres (Mason et al. 1998). This investigation considered both speckle measurements and published data on radial velocity measurements to determine the overall binary properties among stars in clusters and associations, field O-stars, and runaway O-stars. The results indicated a much higher incidence of binaries among O-stars in clusters and associations, and we suggested that the true binary frequency may reach 100% among cluster stars once account is made for the observational bias against detection of binaries with periods larger than those found spectroscopically but smaller than those found through high angular resolution measurements. This work was complemented by similar speckle interferometric surveys of Wolf-Rayet stars (Hartkopf et al. 1999) and Be stars (Mason et al. 1997b).

Ten years later (and armed with an improved detector) we decided it was an opportune time for follow up and expanded speckle observations. A second epoch survey is desirable for a number of reasons. Some systems observed in 1994 may have been situated in orbital phases of close separation, and hence were unresolved. Since the systems detectable by speckle correspond to periods of decades for massive stars, it is important to repeat the survey after a similar time span. Furthermore, there are a significant number of specific systems where new observations are particularly important. For example, there are several cases where a triple is indicated by spectroscopy, but we have yet to resolve the wide system (e.g., δ Cir; Penny et al. 2001). The placement of many of the very hot, O2 and O3 stars in the Hertzsprung–Russell diagram suggests that they are very massive because they are so bright, but sometimes this extreme luminosity is instead due to the presence of a companion (Nelan et al. 2004; Niemela & Gamen 2005; Maíz-Apellániz et al. 2007). The massive binaries in the Orion Trapezium detected in the near-IR by Schertl et al. (2003) have separations that are within

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the resolution limit of a 4 m telescope, and detection or not of these companions at another wavelength can help set limits on the magnitude difference Δm, the color, and hence object type. For systems with two speckle measurements, a third one may allow the motion to be recognized as either linear or nonlinear (i.e., Keplerian), indicating whether the pair is optical or physical. This is extremely important in the case of ι Ori, where dynamical analysis (Gualandris et al. 2004) of this complex runaway system virtually requires that the speckle companion (first reported in Mason et al. 1998 at only 0″.11 separation) be optical rather than physical. Finally, such high angular resolution measurements can provide direct astrometric orbits (for the nearby systems) and hence mass measurements for binaries that are clearly noninteracting (Vanbeveren et al. 1998). These provide fundamental data on the masses and other properties of the most massive stars.

For all these reasons, we embarked on a new survey of speckle interferometry measurements of the massive stars that were mainly selected from the Galactic O-star Catalog (Maíz-Apellániz et al. 2004). We describe the observational program in Section 2 and outline the main tabular results in Section 3. We use these results to reassess the binary properties of the O-stars in Section 4, and then we discuss the results for specific targets in Section 5. The observational program included a significant number of other, less-massive stars, and these measurements and several updated astrometric orbits are given in Appendices A and B, respectively.

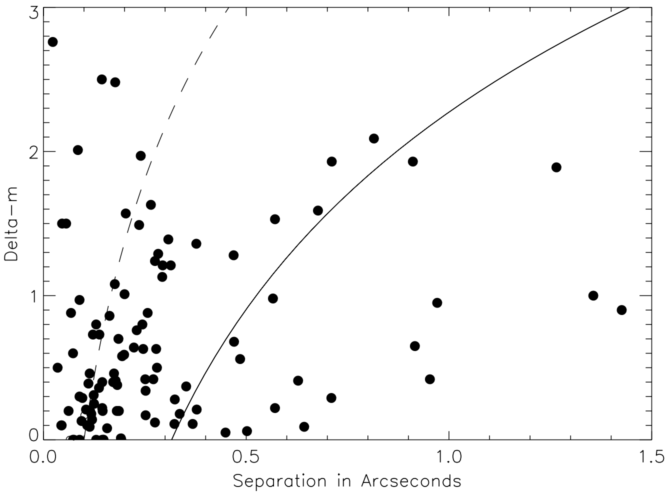

Figure 1. Plot of separation (ρ) vs. magnitude difference (Δm) for pairs observed. The separations are direct measurements from Tables 2 and A1 while Δm is the tabulated value from WDS (Mason et al. 2001). The curved lines indicate the measure of difficulty relationship of Öpik (1924) as modified by Heintz (1978a). The ρ–Δm combinations below the solid line are considered completely known. Those above the dashed line are considered virtually unknown. The filled circles are those objects observed to investigate detection capabilities. The quality of data exceeded expectation. The most challenging object, 22430+3013 or BLA 11Aa, at upper left, has a measured separation of 0″.051 and a magnitude difference of 2.76 (as determined by the Mark III optical interferometer; Hummel et al. 1998).

2. INSTRUMENTATION AND CALIBRATION

The instrument used for most of these observations was the USNO speckle interferometer, described most recently by Hartkopf et al. (2008). Three different filters were selected, all having approximately the same central wavelength but with different full width at half-maximum (FWHM) band passes. Of these, two are standard filters (Strömgren *y*, 550 ± 24 nm, and Johnson *V*, 545 ± 85 nm). An intermediate filter, designated USNO green (560 ± 45 nm), was also used. While the Johnson *V* allows the camera to observe much fainter targets, the resolution limit is degraded to about 0″.05. Both of the other filters reached the goal resolution limit of 0″.03. We selected a filter for each target with a bandwidth suitable to the magnitude of the star and which allowed us to detect an adequate number of speckles. These resolution limit values are most significant when no companion was detected. Instances when the wider Johnson filter was used are indicated with a note to these tables.

Observations of northern hemisphere objects were obtained with the Kitt Peak National Observatory (KPNO) 4 m Mayall reflector during the period 2005 November 8–13; southern hemisphere pairs were observed at the Cerro Tololo Inter-American Observatory (CTIO) 4 m Blanco reflector during the period 2006 March 9–13. Atmospheric conditions during both runs were exceptional, with excellent transparency and significant periods of subarcsecond seeing with both telescopes, especially at Cerro Tololo. On these two runs, 1876 observations were obtained, resulting in 652 measures of double stars and 1050 high-quality observations where a pair was definitively not seen. The remaining observations were of insufficient quality for a definitive measure. Additional observations of massive stars were obtained during other 4 m observing runs as listed below.

Calibration of the KPNO data was determined 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 well-known experiment of Young allowed the determination of scale and position angle zero point 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°.11 in the position angle zero point and 0.165% in the scale error. These "internal errors" are undoubtedly underestimates of the true errors of these observations. Plate scales for the five Kitt Peak runs, 2001 January, 2001 July, 2005 November, 2007 August, and 2008 June, were found to be 0.01257, 0.01282, 0.01095, 0.01090, and 0.01096 arcseconds pixel^{-1}, respectively. While the camera remained the same for all five runs, the latter three were obtained with a newer computer and frame grabber and a different set of microscope objectives. The effective field of view for the detection of binaries is 1″.5 for nominal conditions and 3″.0 when the targets are fainter and a lower microscope objective is used with the Johnson *V* filter. Wider, easily detected pairs can be accommodated with a larger 6″.0 field of view with a low-power microscope objective and 2×2 pixel averaging.

Since the slit-mask option was not available on the CTIO 4 m telescope, we calibrated the southern hemisphere data using observations of numerous well-observed, wide, and equatorially located binaries that we observed with both the KPNO and CTIO telescopes. Published orbital elements for these pairs were updated as needed using the recent KPNO 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 point. The calibration errors for these southern observations were (not surprisingly) considerably higher than those achieved using the slit mask. Mean errors for three CTIO runs from 2001 to 2006 were 0°.67 in position angle and 1.44% in scale. Plate scales for the three Cerro Tololo runs, 2001 January, 2001 July, and 2006 March, were 0.01262, 0.01253, and 0.01084 arcseconds pixel^{-1}, respectively. The differences

Table 1
Newly Resolved Pairs

Coordinates α, δ (2000)	Discoverer Designation	Other Designation	Spectral Classification	V_{AB} (mag)	Notes
031959.27+653908.3	WSI 51 Aa,Ab	HD 20336	B2.5 Vne	4.73	
034716.57+240742.3	WSI 52 Da,Db	HD 23608	F3 V	8.72	1
042837.00+191049.6	WSI 53 Aa,Ab	ϵ Tau	G9.5 III	3.54	2
075220.28−262546.7	WSI 54	HD 64315	O6 Vn	9.23	
080929.33−472043.0	WSI 55 Ba,Ab	HD 68243	B1 IV	4.20	Section 5.4
104512.87−594419.2	WSI 56	CPD−59 2636	O8 V	9.29	
131345.52−633511.8	WSI 57	HD 114737	O9 III	8.00	Section 5.4
131444.39−633451.8	WSI 58 Aa,Ab	HD 114886	O9 II–III	6.86	Section 5.4
141501.61−614224.4	WSI 59 Ba,Ab	HD 124314B	. . .	8.66	3, Section 5.4
171905.50−384851.2	WSI 60	CD−38 11748	O4 If+	11.17	
171946.16−360552.3	WSI 61 Ba,Ab	HD 319703B	O6.5 V	11.34	Section 5.4
172444.34−341156.6	WSI 62 CD	HD 319718C	. . .	. . .	Section 5.4
172444.34−341156.6	WSI 62 CE	HD 319718C	. . .	. . .	Section 5.4
175136.72−163236.3	WSI 63 AB	TYC 6249-233	. . .	11.75	4, 5
175136.72−163236.3	WSI 63 AC	TYC 6249-233	. . .	11.75	5
175331.95−162247.0	WSI 64	GSC S81N021274	. . .	13.28	5
180015.80+042207.0	WSI 65	66 Oph	B2 Ve	4.78	
203308.78+411318.1	WSI 66	Cyg OB2-22	O3 If* + O6 V((f))	11.68	Section 5.4
203323.46+410912.9	WSI 67	Cyg OB2-841	O5.5 V	11.89	

Notes. (1) Spectroscopic triple noted by G. Torres (2006, private communication). Not examined in the earlier speckle survey of the Pleiades (Mason et al. 1993a). (2) Companion not detected in the earlier speckle survey of the Hyades (Mason et al. 1993b). (3) A new close pair associated with the B component of this multiple system. The precise coordinates above are for the A component. (4) New companion was "preconfirmed" with 2MASS data.[6] (5) This was a possible occultation target for the New Horizons mission.

are attributable to changes in equipment as described above. The field of view was comparable for the southern and northern observations.

Speckle interferometry is a technique which is very sensitive to changes in observing conditions, particularly coherence length (ρ_0) and time (τ_0). These are typically manifested as a degradation of detection capability close to the resolution limit or at larger magnitude differences. To ensure we are reaching our desired detection thresholds, a variety of systems with well-determined morphologies and magnitude differences were observed throughout every observing night. In all cases, the observations of these test objects indicated that our measurements met or exceeded these thresholds, as indicated in Figure 1.

3. RESULTS

The target list consists of the original sample of O-stars from Mason et al. (1998), additional O-stars from the catalog of Maíz-Apellániz et al. (2004), WR stars, and B-stars. The B-star sample includes candidates for orbit and mass determination, Pleiades cluster members observed previously (Mason et al. 1993a), and Be stars (Mason et al. 1997b). A number of low-mass targets were also observed that are discussed in Appendix A.

Table 1 presents coordinates and magnitude information from CDS[5] for all those binaries which are resolved or measured for the first time. Column 1 gives the coordinates of the primary of the pair. Column 2 lists the discoverer designation number (with WSI = Washington Speckle Interferometry), and Column 3 gives an alternative designation. Column 4 provides the spectral classification, and Column 5 the combined visual magnitude. Finally, Column 6 refers to notes below the table.

Table 2 lists the astrometric measures of the observed massive binaries. They are subdivided into four groups consisting of the original 1998 sample of O-stars, the newer set of O-stars, WR stars, and B-stars. The first three columns identify the system by providing the epoch-2000 coordinates, discovery designation, and an alternate designation. Columns 4–6 give the epoch of observation (expressed as a fractional Besselian year), the position angle θ (in degrees), and the separation ρ (in seconds of arc). Note that the position angle has not been corrected for precession, and is thus based on the equinox for the epoch of observation. Objects whose measures are of lower quality are indicated by colons following the position angle and separation. These lower-quality measurements may be due to one or more of the following factors: close separation, large Δm, one or both components very faint, a large zenith distance at the time of observation, and poor seeing or transparency. They are included primarily because they confirm an earlier observation or because a long time has elapsed since the last measurement. Column 7 provides the V-band magnitude difference. This is usually a catalog value from the Washington Double Star Catalog (WDS; Mason et al. 2001), although for new pairs and some other infrequently measured interferometric pairs it is a crude value based upon the strengths of the secondary peak and "anti-peak" in Fourier Transform space, as seen in the generated directed vector autocorrelations (Bagnuolo et al. 1992). Differential magnitudes were "calibrated" by direct comparison with other pairs of known magnitude difference and are probably accurate to ±0.5 mag. Column 8 indicates the number of observations used to derive the mean position (usually 1). For systems with orbits, the observed minus calculated residuals $O-C$ for both θ and ρ are given in Columns 9 and 10 according to the orbit whose reference is given in Column 11. Finally, Column 12 refers to specific notes for these systems. Some measures from other KPNO/CTIO 4 m runs are noted and listed here and in Table 3.

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[5] Magnitude information is from the Aladin Sky Atlas, operated at CDS, Strasbourg, France.

[6] 2003 all-sky release http://pegasus.phast.umass.edu/.

Table 2
Speckle Interferometric Measurements of Double Stars

WDS Designation $\alpha\delta$ (2000)	Discoverer Designation			Other Identifier	Epoch (BY)	θ (deg)	ρ ($''$)	Δm (mag)	n	$[O-C]_\theta$ (deg)	$[O-C]_\rho$ ($''$)	Reference	Notes
				Original Sample O-Stars									
02407+6117	CHR	208	Aa,Ab	HD 16429	2005.8628	270.7	0.277	2.7	1				3
05297+3523	HU	217		HD 35921	2005.8634	252.9	0.608	1.2	1				
05320−0018	HEI	42	Aa,Ab	δ Ori	2001.0822	133.9	0.297	1.4	1	2.6	−0.021	Section 5.2	
					2005.8662	133.3	0.318		1	0.1	0.006	Section 5.2	
					2006.1909	132.6	0.310		1	−0.5	−0.002	Section 5.2	
05354−0525	CHR	249	Aa,Ab	HD 37041	2005.8662	278.9	0.392	3.2	1				
					2006.1910	293.3	0.380		1				
05354−0555	CHR	250	Aa,Ab	ι Ori	2005.8662	111.7 :	0.131 :	2.4	1	1.4	0.003	Section 5.1	3
					2006.1936	109.7	0.127		1	−0.3	−0.001	Section 5.1	
05387−0236	BU	1032	AB	σ Ori	2005.8662	96.9	0.254	1.2	1	−1.3	0.004	Turner et al. (2008b)	
					2006.1910	96.8	0.247		1	−0.6	−0.003	Turner et al. (2008b)	
06410+0954	CHR	168	Aa,Ab	15 Mon	2001.0197	231.1	0.061	1.2	1	−110.1	0.022	Gies et al. (1997)	1, Section 5.5
					2005.8635	242.2	0.104		1	−117.6	0.047	Gies et al. (1997)	1
					2006.1909	251.9	0.089		1	−108.8	0.032	Gies et al. (1997)	1
07187−2457	FIN	313	Aa,Ab	τ CMa	2006.1937	125.2	0.128	0.4	1				
08095−4720	WSI	55	Ba,Bb	HD 68243	2006.1882	273.6 :	0.085 :	1.5	1				2, 3, Section 5.4
08392−4025	B	1623		HD 73882	2006.1884	254.4	0.662	1.3	1				
10440−5933	NEL	1	Aa,Ab	HD 93129A	2006.1886	10.1	0.043	0.9	1				
10441−5935	HJ	4360	AB	HD 93161	2006.1886	115.3	1.982	0.1	1				
11383−6322	I	422	AB	HD 101205	2006.1967	113.8	0.357	0.3	2				
11406−6234	CPO	11		HD 101545	2006.1888	219.2	2.543	0.6	1				
13138−6335	WSI	57		HD 114737	2006.1888	235.4	0.188	1.5	1				2, 3, Section 5.4
13147−6335	WSI	58	Aa,Ab	HD 114886	2006.1888	276.9	0.243	1.6	1				2, 3, Section 5.4
14150−6142	WSI	59	Ba,Bb	HD 124314B	2006.1891	245.8	0.208	1.3	1				2, 3, Section 5.4
16466−4705	B	1825	AB	HD 150958	2006.1919	245.1	0.297	1.7	1				
16540−4148	B	1833	AB	HD 152234	2006.1945	75.3	0.513	2.3	1				
16542−4150	CHR	252	Aa,Ab	HD 152248	2006.1945	236.5 :	0.052 :	2.0	1				
16563−4040	HDS	2394		HD 152623	2006.2000	307.4	0.238	1.3	1				
16569−4031	CHR	254	Aa,Ab	HD 152723	2006.2000	125.6	0.098	1.7	1				3, 4
17158−3344	SEE	322		HD 155889	2006.1945	282.2	0.189	0.6	1	−0.7	0.005	Turner et al. (2008b)	
18152−2023	CHR	255	Aa,Ab	HD 167263	2006.1946	149.7	0.069	2.0	1				3
20074+3543	STT	398	AB	HD 191201	2005.8679	82.4	0.971	1.8	1				
20181+4044	CHR	96	Aa,Ab	HD 193322	2005.8652	100.4	0.086	1.2	1	−5.6	0.019	Hartkopf et al. (1993)	1, 3, Section 5.5
					2007.6042	100.8	0.067		1	−14.3	0.005	Hartkopf et al. (1993)	1
					2008.4508	116.7	0.066		1	−3.2	0.005	Hartkopf et al. (1993)	1
	STF	2666	AB		2001.4991	245.7	2.713	1.3	1				
20189+3817	A	1425	AB	HD 193443	2005.8652	258.7	0.126	0.3	1				
21390+5729	MIU	2	Aa,Ab	HD 206267	2005.8654	247.9	0.118	1.1	1				3

Table 2
(Continued)

WDS Designation $\alpha\delta$ (2000)	Discoverer Designation			Other Identifier	Epoch (BY)	θ (deg)	ρ ($''$)	Δm (mag)	n	$[O-C]_\theta$ (deg)	$[O-C]_\rho$ ($''$)	Reference	Notes
New Sample O-Stars													
02512+6023	BU	1316	AB	HD 17520	2005.8620	297.8	0.309	0.5	2				
05228+3325	BU	887	AB	BD+331026	2005.8635	195.1	1.089	0.8	1				
07523−2626	WSI	54		HD 64315	2006.1937	231.8	0.091	0.2	1				2, 3
10452−5944	WSI	56		CPD−592636	2006.1886	59.8	0.269	0.6	1				2, 3
11151−6116	B	1184	AB-F	HD 97950	2006.1967	293.7	5.005	2.8	1				
15557−5439	HDS	2241		CPD−546791	2006.1970	284.9	1.132	0.4	1				
17191−3849	WSI	60		CD−3811748	2006.1971	333.1	1.325	1.2	1				2, 3
17198−3606	WSI	61	Ba,Bb	HD 319703B	2006.1971	15.8	0.188	1.5	1				2, 3, Section 5.4
17247−3412	DAW	216	BC	HD 319718B	2006.1971	319.8	4.722	1.4	1				
	WSI	62	CD	HD 319718C	2006.1971	204.1 :	3.400 :	2.0	1				2, 3, Section 5.4
			CE	HD 319718C	2006.1971	182.0	3.628	2.8	1				2, 3, Section 5.4
18186−1348	DCH	26		HD 168076	2006.2001	314.0	0.144	0.7	1				3
20316+4113	ES	1679		BD+404212	2005.8680	214.1	3.518	2.6	2				Section 5.5
20331+4113	WSI	66		Schulte22	2005.8680	147.0	1.380	0.4	1				2, 3, Section 5.4
					2007.6018	144.1	1.502		1				2
					2008.4587	145.7	1.509		1				2
20334+4109	WSI	67		Schulte841	2005.8680	323.3	0.669	0.4	1				2, 3
					2007.6018	322.8	0.716		1				2
					2008.4589	323.9	0.713		1				2
Wolf-Rayet Pairs													
04566−6629	DON	89	AB	HD 32228	2006.1963	189.9	1.080	0.1	2				
			AC		2006.1963	11.4	2.355	1.8	1				
			AD		2006.1963	233.7	2.271	1.3	2				
	HJ	3716	AE		2006.1963	291.3	4.651	0.7	1				
	DON	90	EF		2006.1963	340.1	1.272	1.0	1				
15150−5951	HDS	2142		WR66	2006.1970	14.2 :	0.398 :	1.1	1				4
20358+4123	NML	1		WR146	2001.4993	16.8	0.157	0.4	1				Section 5.5
					2008.4587	14.5	0.136		1				
20367+4021	NML	2		WR147	2001.4991	350.7	0.627	2.2	1				Section 5.5
					2008.4589	349.4	0.631		1				
B Stars													
00165+6308	TDS	1374		BD+6237	2007.6074	257.6	0.549	0.2	1				4
00186+6351	TDS	1392		BD+6324	2007.6074	359.0 :	0.185 :	0.1	1				4
00221+6211	HDS	49		HD 1743	2007.6074	238.2	0.319	2.2	1				4
00243+5201	HU	506		HD 1976	2005.4315	90.0	0.112	0.9	2	1.2	0.002	Docobo & Andrade (2005)	
					2007.6021	94.3	0.110		1	−2.2	0.004	Docobo & Andrade (2005)	
00318+5431	STT	12		HD 2772	2007.6021	203.2	0.286	0.3	1	−3.7	0.077	Ling et al. (2005)	
00507+6415	MCA	2		HD 4775	2007.6021	174.5	0.053	1.1	1	8.5	0.008	Mason et al. (1997a)	
00529+6053	TDS	1655		TYC 4017-325-1	2007.6075	78.1	0.414	0.1	1				4
00568+6022	BU	1099	AB	HD 5408	2005.8614	357.4	0.273	0.4	2	−1.8	−0.014	Cole et al. (1992)	a
					2007.6035	0.1	0.265		2	−2.2	−0.015	Cole et al. (1992)	

Table 2
(Continued)

WDS Designation $\alpha\delta$ (2000)	Discoverer Designation			Other Identifier	Epoch (BY)	θ (deg)	ρ ($''$)	Δm (mag)	n	$[O-C]_\theta$ (deg)	$[O-C]_\rho$ ($''$)	Reference	Notes
02039+4220	STT	38	BC	HD 12534	2005.8615	100.3	0.351	1.2	2	−2.2	−0.007	Docobo & Ling (2007a)	
					2007.6021	99.3	0.299		1	−2.2	−0.015	Docobo & Ling (2007a)	
02145+6631	MCA	6		HD 13474	2007.6021	295.4	0.109	1.2	1	−32.7	0.020	Hartkopf et al. (2000)	
02257+6133	STF	257		HD 14817	2007.6021	71.0	0.416	0.7	1	2.8	−0.027	Zaera (1985)	
02529+5300	A	2906	AB	HD 17743	2005.8601	120.0	0.237	1.5	3				
	STF	314	AB-C		2005.8610	313.3	1.554	0.3	2				
03082+4057	LAB	2	Aa,Ab	β Per	2007.6022	143.3 :	0.049 :	2.5	1	1.0	0.006	Pan et al. (1993)	
03200+6539	WSI	51	Aa,Ab	HD 20336	2007.6022	43.7	0.132	1.2	1				3
03272+0944	HDS	433		HD 21364	2005.8616	53.8	0.224	3.8	2	−6.9	−0.012	Romero (2007)	
03284+6015	A	980	AB	HD 21203	2007.6022	337.9	0.364	1.6	1	−2.9	0.003	Baize (1994)	
04422+2257	MCA	16	Aa,Ab	τ Tau	2005.8690	39.2	0.314	2.4	1	1.2	0.023	Olevic & Cvetkovic (2005b)	
05145−0812	BU	555	BC	HD 34085	2005.8662	29.8 :	0.124 :	0.1	1				
05245−0224	MCA	18	Aa,Ab	η Ori	2006.1908	302.8	0.066	1.3	1	−2.1	0.005	Olevic & Jovanovic (1998)	3
05245−0224	DA	5	AB		2005.8662	77.4	1.715	1.3	1				
					2006.1908	78.1 :	1.768 :		1				
05272+1758	MCA	19	Aa,Ab	HD 35671	2005.8635	88.5	0.104	1.0	1	−20.1	0.030	Olevic & Jovanovic (1997)	
										−1.5	0.000	Mason (1997)	5
05308+0557	STF	728		HD 36267	2001.0197	46.3	1.146	1.3	1	0.4	−0.036	Seymour & Hartkopf (1999)	
					2001.0767	45.7	1.140		1	−0.2	−0.043	Seymour & Hartkopf (1999)	
					2001.0823	46.8	1.150		1	0.9	−0.033	Seymour & Hartkopf (1999)	
05354−0425	FIN	345		HD 37016	2006.1910	95.8	0.394	2.3	1				
07003−2207	FIN	334	Aa,Ab	HD 52437	2006.1938	342.4	0.096	0.0	1	12.6	−0.012	Mante (2002)	6
										12.1	−0.014	Olevic (2002a)	6
										7.5	−0.024	Olevic (2002a)	6
07143−2621	FIN	323		HD 56014	2006.1937	153.4	0.115	0.5	1	2.1	−0.089	Olevic & Cvetkovic (2004)	1
07374−3458	FIN	324	AB	HD 61330	2006.1884	174.5	0.271	0.5	1				
08144−4550	FIN	113	AB	HD 69302	2006.1992	73.2	0.122	1.6	1				
08250−4246	CHR	226	Aa,Ab	HD 71302	2006.1884	277.1	0.044	1.1	1				
	RST	4888	AB		2006.1884	104.9	0.514	0.2	1				
08280−3507	FIN	314	Aa,Ab	HD 71801	2006.1992	213.8	0.083	0.8	1				
08291−4756	FIN	315	Aa,Ab	HD 72108	2006.1938	187.2	0.095	0.5	2				
08328−4153	HDS	1222		HD 72731	2006.1992	302.1	0.557	0.9	2				4
09125−4337	FIN	317	Aa,Ab	HD 79416	2006.1884	102.3	0.123	0.5	1				
09128−6055	HDO	207	AB	HD 79699	2006.1939	79.7	0.164	0.3	2	−16.7	0.031	Heintz (1996a)	1
09569−6323	FIN	151		HD 86557	2006.1993	347.0	0.865	1.6	1				
10050−5119	HU	1594		HD 87652	2006.1940	311.7	0.163	0.4	1	2.9	−0.039	Seymour et al. (2002)	
10465−6416	FIN	364		HD 93549	2006.1940	138.8	0.069	0.1	1	17.1	−0.095	Mante (2003b)	1
11210−5429	I	879		π Cen	2006.1887	158.7	0.215	1.6	1	−1.8	0.001	Mason et al. (1999)	a
11248−6708	HDS	1623		HD 99317	2006.1995	112.1	0.168	0.8	1				4
11286−4508	I	885		HD 99804	2006.1887	152.8	0.647	0.4	2	5.0	0.086	Seymour et al. (2002)	1

Table 2
(Continued)

WDS Designation $\alpha\delta$ (2000)	Discoverer Designation			Other Identifier	Epoch (BY)	θ (deg)	ρ ($''$)	Δm (mag)	n	$[O-C]_\theta$ (deg)	$[O-C]_\rho$ ($''$)	Reference	Notes
11309−6019	HDS	1631		HD 100135	2006.1995	3.0	0.181	0.5	1				4
11325−6137	B	1700		CPD−603034	2006.1995	257.6	0.554	1.4	1				
11327−6552	NZO	23		HD 100431	2006.1995	234.8	0.964	0.5	1				
11389−7053	B	1703		HD 101317	2006.1995	323.1	0.525	0.2	1				
12068−7304	HDS	1709		HD 105196	2006.1996	80.8	0.117	1.0	1				4
12093−6606	HDS	1715		HD 105545	2006.1996	90.1	0.132	1.9	1				4
12325−5954	JSP	539		HD 109091	2006.1996	201.2	0.179	0.7	1				
12332−6057	B	802		HD 109164	2006.1996	175.2	0.464	1.4	1				
12450−6519	HDS	1785		HD 110737	2006.1996	236.7	0.231	0.9	1				4
12499−6437	HDS	1800		HD 111409	2006.1996	46.5	0.103	0.7	1				4
13032−5607	FIN	64		HD 113237	2006.1998	259.3	0.499	1.2	1				
13123−5955	SEE	170	AB	HD 114529	2006.1942	104.3	0.267	0.7	1	1.4	0.054	Finsen (1964)	1
13134−5042	I	1227		HD 114772	2006.1998	336.6	0.320	0.2	1				
13218−5525	I	924		HD 115990	2006.1998	96.4	0.716	0.6	1				
13345−4816	RST	4985		HD 117919	2006.1997	150.3	0.287	1.9	1				
13437−4204	FIN	353	AB	HD 119361	2006.1997	50.0	0.096	1.2	1				
14567−6247	FIN	372		θ Cir	2006.1917	22.8	0.098	0.0	2	10.2	−0.093	Mante (2003c)	1
15088−4517	SEE	219	AB	λ Lup	2006.1998	51.1	0.130	0.8	1	13.4	−0.030	Docobo & Ling (2007a)	a
15122−1948	B	2351	Aa,Ab	ι Lib	2006.1918	11.9	0.154	0.4	1	−0.9	−0.006	Mason et al. (1999)	a
					2008.4556	352.4	0.155		1	−0.7	−0.003	Mason et al. (1999)	
15234−5919	HJ	4757		γ Cir	2006.1892	5.2	0.808	0.8	2	13.6	0.001	Nys (1982)	6
										1.3	0.043	Ling et al. (2005)	6
15246−4835	B	1288	AB	HD 136807	2006.1998	347.1	0.071	0.1	1	3.0	−0.024	Seymour et al. (2002)	
15329+3122	COU	610		θ CrB	2008.4489	198.8	0.809	2.0	2				
15351−4110	HJ	4786		γ Lup	2006.1927	275.7	0.789	1.5	3	−1.7	−0.028	Heintz (1990)	1
15416+1940	HU	580	AB	ι Ser	2006.2000	262.3	0.092	0.1	1	−0.1	−0.003	Docobo & Ling (2007a)	a
16003−2237	LAB	3		δ Sco	1988.2528	7.9 :	0.115 :	2.2	1	−0.5	−0.009	Section 5.3	7
					1990.2705				2	322.5	0.040	Section 5.3	8
					1990.3439				2	326.2	0.048	Section 5.3	8
					1993.0988	349.0	0.170		1	−0.6	−0.003	Section 5.3	7
					2001.5667	337.0	0.080		1	−0.6	−0.004	Section 5.3	

Table 2
(Continued)

WDS Designation $\alpha\delta$ (2000)	Discoverer Designation			Other Identifier	Epoch (BY)	θ (deg)	ρ ($''$)	Δm (mag)	n	$[O-C]_\theta$ (deg)	$[O-C]_\rho$ ($''$)	Reference	Notes
					2004.2017	348.9	0.183		1	−2.0	0.003	Section 5.3	9
					2006.1918	354.4	0.187		1	−1.8	−0.005	Section 5.3	
					2006.5554	357.5	0.176		1	0.2	−0.014	Section 5.3	10
					2007.3173	359.8	0.194		1	0.5	0.012	Section 5.3	
16120−1928	BU	120	AB	HD 145502	2006.1945	1.6	1.330	1.0	1				
	MTL	2	CD	HD 145502C	2006.1971	54.4	2.293	0.6	1				
16341+4226	LAB	4		σ Her	2007.6068	17.3	0.102	3.5	1	0.3	−0.008	Brendley & Hartkopf (2007)	
					2008.4612	14.9	0.113		1	2.1	0.001	Brendley & Hartkopf (2007)	
17237+3709	MCA	48	Aa,Ab	ρ Her	2007.6041	32.0 :	0.248 :	1.0	1				3
					2008.4613	31.9	0.252		1				
17400−0038	BU	631		HD 160438	2006.2000	89.0	0.246	0.2	1	1.8	−0.019	Heintz (1996c)	a
18003+0422	WSI	65		HD 164284	2007.5879	155.4	0.121	1.5	1				
18262−1832	CHR	236		HD 169602	2007.5880	113.1 :	0.143 :	1.5	1				4
18280+0612	CHR	71		HD 170200	2007.5879	290.1	0.080	0.1	1	3.7	0.002	Mason & Hartkopf (2001b)	3
18454+3634	HDS	2659		HD 173761	2007.6069	21.9	0.245	2.4	1				4
18520+1358	CHR	80		HD 174853	2007.5878	36.4	0.126	2.3	1				3
19070+1104	HEI	568		HD 178125	2008.4508	272.4	0.308	1.0	1				
19411+1349	KUI	93		HD 185936	2005.8680	318.0	0.189	0.1	1	3.1	0.009	Docobo & Ling (2007a)	
20393−1457	HU	200	AB	τ Cap	2005.8680	123.0	0.336	1.9	1	3.9	0.007	Heintz (1998)	
20474+3629	STT	413	AB	HD 198193	2005.8572	4.0	0.881	1.5	2	0.1	−0.020	Rabe (1948)	
					2007.6018	4.1	0.869		1	0.9	−0.035	Rabe (1948)	
20598+4731	MCA	65	Aa,Ab	HD 200120	2007.6018	2.3	0.169	2.8	1				
					2008.4509	1.8	0.164		1				
21028+4551	BU	1138	AB	HD 200595	2001.5018	175.6	0.073	0.2	1	−19.1	0.015	Hartkopf & Mason (2001b)	
21100+4901	HDS	3016		BD+483298	2007.6072	23.4	0.329	1.4	1				4
21118+5959	MCA	67	Aa,Ab	HD 202214	2005.8654	124.5	0.045	0.6	1	4.0	−0.001	Mante (2002)	
	STF	2780	AB		2005.8654	212.4	1.021	0.3	1				
					2007.5990	212.5	1.013		2				
21126+3846	COU	2136		BD+384391	2007.6072	292.8	0.422	0.9	1				4

Table 2
(Continued)

WDS Designation $\alpha\delta$ (2000)	Discoverer Designation			Other Identifier	Epoch (BY)	θ (deg)	ρ ($''$)	Δm (mag)	n	$[O-C]_\theta$ (deg)	$[O-C]_\rho$ ($''$)	Reference	Notes
21157+4832	HDS	3024		BD+473349	2007.6072	329.6	0.283	1.9	1				4
21191+6152	HDS	3035	Aa,Ab	HD 203374	2007.6073	296.5	0.294	2.3	1				4
21287+7034	LAB	6	Aa,Ab	β Cep	2007.5990	226.0	0.172	3.4	1				
21323+5934	HDS	3062		HD 205329	2007.6073	285.2	0.110	1.7	1				4
21340+6029	HDS	3071		HD 239700	2007.6073	291.1	0.143	1.7	1				4
21428+6018	HDS	3093		HD 239743	2007.6073	267.3	0.140	1.6	1				4
21536−1019	FIN	358		HD 208008	2007.5992	308.3	0.130	2.0	1	1.2	−0.011	Mason & Hartkopf (2001a)	
23019+4220	WRH	37	AB	HD 217675	2005.8625	217.8	0.109	2.3	1	−12.7	0.009	Hartkopf et al. (1996)	
										5.4	0.008	Olevic & Cvetkovic (2006)	5
					2007.5884	204.9	0.128		1	−13.7	0.008	Hartkopf et al. (1996)	
										3.7	0.005	Olevic & Cvetkovic (2006)	
23078+6338	HU	994		HD 218537	2005.8625	136.1	0.207	0.3	1	3.9	−0.045	Docobo (1991)	
23165+6158	HDS	3314		HD 219634	2007.5884	320.3	0.176	2.6	1				

Notes. (a) System used in characterizing errors or investigating detection space. (1) Orbit in obvious need of correction. (2) Not measured before (Table 1). (3) Δm is an estimate, not a catalog value. (4) Confirming observation. (5) While the 6th Orbit Catalog lists two possible solutions for this pair, it fits the second orbit listed here better. (6) Multiple possible orbits for this pair, none of which fit well. While correction may be necessary, the data coverage may be insufficient. (7) Unpublished CHARA speckle measure. See Hartkopf et al. (2000) for a description of the CHARA speckle camera and a discussion of re-reduced observations. (8) Unpublished CHARA nondetection. See Hartkopf et al. (2000). The $O-C$ columns here provide the position predicted by the new orbit. (9) Measure obtained with the NOFS 61 inch reflector. Inadvertently omitted from Hartkopf et al. (2008). (10) Measure obtained with the Mt. Wilson 100 inch reflector (W. Hartkopf & B. Mason 2009, in preparation) .

(This table is also available in machine-readable and Virtual Observatory (VO) forms in the online journal.)

Table 3
Null Companion Detection[a]

R.A., Decl. (2000) (hhmmss.ss±ddmmss.s)	Cluster, Other Designation	V*, **, Other Designation	HD, HIP, Other Designation	List Code	Date (BY)	Telescope Code	Notes
000357.50+610613.0	BD+60 2663		HD 225146	O2	2005.8625	K	
000403.79+621319.0	BD+61 2585		HD 225160	O2	2005.8625	K	
000603.38+634046.7	EM* MWC 1	V* NSV 25	HD 108	O1	2005.8626	K	
001743.06+512559.1	BD+50 46A	V* AO Cas	HD 1337	O1	2005.8626	K	
004443.51+481703.7	EM* MWC 8	V* omi Cas	HD 4180	B*	2007.6021	K	
005249.21+563739.4	BD+55 191	** BU 1A	HD 5005	O1	2005.8626	K	1
013113.41+604659.9	BD+60 252		TYC 4031 00248 1	B*	2005.8625	K	
013232.72+610745.8	BD+60 261		TYC 4031 01953 1	O2	2005.8626	K	
014052.75+641023.1	BD+63 218		HD 10125	O2	2005.8626	K	
020230.12+553726.3	BD+54 441	V* NSV 702	HD 12323	O2	2005.8626	K	

Notes. Observing list code—B*: B star sample; O1: Mason et al. (1998) O-star sample; O2: new O-star sample; W1: Hartkopf et al. (1999) WR sample; W2: additional WR stars observed. Telescope code—C: CTIO 4 m; K: KPNO 4 m. (1) Observed one component of a wide double/multiple. (2) The known close companion may have closed such that $\rho < 0\farcs03$. (3) The known companion has too large a magnitude difference for detection here. (4) Observed with a Johnson *V* filter and usually a lower magnification microscope objective due to the character of the target. The resolution limit for this observation is estimated at $\rho < 0\farcs05$. (5) The known companion is too faint for detection here. (6) Observed with the USNO *g* filter ($\lambda_{\rm eff} = 560$ nm, FWHM $= 45$ nm). This filter has the same color as the Strömgren *y* filter and is still fairly narrow, so the resolution limit is essentially the same ($\sim 0\farcs03$). (p) Pleiades cluster member (Mason et al. 1993a).

[a] $\rho < 0\farcs03$ except as noted.

(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.)

Table 4
Binary Properties of Galactic O-Stars

Star Name	Spectroscopic Status	No. Vis. Comp.	Environment	Runaway?	Spectroscopic Reference
HD 164019	C	1	Field:	no:	1957MmRAS..68....1F
HD 162978	C	1	Sgr OB1	no	1980ApJ...242.1063G
HD 168941	C	1	Field:	yes	1957MmRAS..68....1F
Herschel 36	U	1	NGC 6530,Sgr OB1	no	1997AJ....113..823R
9 Sgr	SB2?	1	Sgr OB1	no	2002A&A...394..993R
HD 164816	SB2?	1	Sgr OB1	no	2006MNRAS.366..739A
HD 165052	SB2O	1	Sgr OB1	no	2007A&A...474..193L
ζ Oph	C	1	Sco OB2	yes	2005ApJ...623L.145W
HD 165246	SBE	2	Sgr OB1	no	2007OEJV...72....1O

(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.)

Table 3 provides a complete list of single star observations for the massive star sample. The precise coordinate (α, δ) is given in Column 1, while Columns 2–4 list various designations. A code for the massive star subsample is given in Column 5, and the Besselian date of observation appears in Column 6. Column 7 indicates with a K or C if the 4 m telescope used for the observation is the Mayall reflector at KPNO (K) or the Blanco reflector at CTIO (C). Finally, Column 8 provides notes for the stars.

4. BINARY FREQUENCY OF O-TYPE STARS

It is important to consider the environment of massive stars in the determination of binary frequency. While most massive stars are found close to their birthplaces in stellar clusters and OB associations, there are significant numbers of "field" O-stars (which have no apparent nearby cluster; de Wit et al. 2005) and "runaway" O-stars (high velocity or remote from the Galactic plane; Gies & Bolton 1986) that were probably ejected from clusters. The ejection process may have involved close gravitational encounters of binaries and/or supernovae explosions in binaries (Hoogerwerf et al. 2000; Zinnecker & Yorke 2007), and such ejected stars will generally be single objects. In our original speckle survey (Mason et al. 1998), we found that indeed the binary fraction decreased among field and runaway O-stars compared to those in clusters and associations.

Here, we revisit the question of the binary frequency of massive stars based upon the results from our speckle interferometric survey. We will restrict our sample to the O-stars appearing in the Galactic O Star Catalog of Maíz-Apellániz et al. (2004), since we now have speckle data for 360 of the 370 stars in the catalog. These stars and their binary properties are listed in Table 4, using the same names and order (based upon increasing Galactic longitude) as given in the Galactic O Star Catalog.

The second column of Table 4 gives a code for the short-period, spectroscopic binary status based upon a literature search through 2008 August. These codes are similar to those adopted by Mason et al. (1998), and we use an "SB" prefix for known or probable spectroscopic binaries, a "C" for constant velocity stars, and a "U" for stars of unknown status (usually with fewer than four radial velocity measurements). The SB stars with a published orbit have an "O" suffix attached to the code and a middle numeral that represents the number of spectral components identified. Usually a code of "SB2O" represents a double-lined spectroscopic binary, but we also apply it to cases such as QZ Car = HD 93206 that consists of two single-lined binaries in a quadruple system. The "SB3O" code is applied to triple systems where a third, stationary, spectral component is visible at the greatest velocity separation of the double-lined system. An "E" suffix denotes the presence of orbital flux variations (eclipses or ellipsoidal variations), and the "SBE" code indicates that we know that the star is a binary from the light curve but no spectroscopic investigation exists yet. The suspected spectroscopic binaries are coded by "SB2?" (where observers report line doubling) and "SB1?" (where the range in measured radial velocity exceeds 35 km s^{-1}). Note that "SB2?" systems are not uncertain in their spectroscopic multiplicity but simply lack complete orbital determination. The most recent published reference is indicated by the SAO/NASA Astrophysics Data System bibliographic code in Column 6 of Table 4.

The number of angularly resolved components is given in Column 3 of Table 4. This represents the sum of the number of close components found by speckle interferometry, wider and fainter components found by Turner et al. (2008b) in an adaptive optics survey, and other (usually wider) components listed in the WDS (Mason et al. 2001). These sources were supplemented by detailed studies of specific stars or clusters, such as ζ Ori (long baseline optical interferometry; Hummel et al. 2000), Trumpler 14 (*HST* FGS; Nelan et al. 2004), the Orion Trapezium (infrared single aperture interferometry; Petr et al. 1998; Simon et al. 1999; Weigelt et al. 1999; Kraus et al. 2007), and NGC 6611 (Duchêne et al. 2001). A quotation mark in this column indicates that the star is a member of a visual system whose primary component also appears in the table (usually just above or below such an entry), and a colon marks those stars that lack speckle observations. Note that a large number of visual components may indicate that the star resides at the center of a dense cluster.

Column 4 of Table 4 associates the star with the field or the name of the home cluster, while Column 5 lists whether or not the star is considered to be a runaway object. These determinations come directly from the Galactic O Star Catalog (Maíz-Apellániz et al. 2004) with new runaway identifications noted by Mdzinarishvili (2004) and de Wit et al. (2005). Note that some runaway stars can be traced to a cluster of origin, so that they will be assigned to that cluster in Column 4.

The binary statistics derived from Table 4 are summarized in Table 5 (an updated version of Table 3 from Mason et al. 1998). We caution that the sample is magnitude limited (and therefore biased to more luminous stars) and incompletely surveyed (for example, the Turner et al. 2008b adaptive optics work is limited to stars with declination $> -42°$). The stars are grouped into cluster/association, field, and runaway categories to compare the binary properties. For the immediate purpose of this work, we simply assigned any star that was not a field or runaway object to the cluster/association category. This includes stars described as more distant than some foreground cluster, since such stars generally reside along a spiral arm of the Galaxy where cluster membership is common. The top section of Table 5 summarizes the visual multiplicity properties of each category for the 347 unique, visual systems in the Galactic O Star Catalog. The results are presented in rows that correspond to the sum based upon the number of visual components n found. We divide the sample into single and multiple groups in determining the percentages without and with companions (making the tacit assumption that most of the visual companions are gravitationally bound and not line-of-sight optical companions).

Table 5
Binary Frequency of Galactic O-stars

Category	Cluster/Association	Field	Runaway
(A) Visual multiplicity			
No. systems	249	56	42
$n = 2$	50	11	9
$n > 2$	58	3	2
Total	43%	25%	26%
$n = 1$	141	42	31
Total	57%	75%	74%
(B) Spectroscopic properties			
No. stars	272	56	42
SB3O	9	0	0
SB2O	38	3	3
SB1O	14	0	5
SBE	5	3	0
SB2?	15	4	1
SB1?	45	8	3
Less SB?	30%	15%	19%
Total	57%	46%	29%
C	97	21	30
Total	43%	54%	71%
U	49	17	0
(C) Fraction with any companion			
Less SB?	66%	41%	37%
Total	75%	59%	43%

The middle section of Table 5 presents the corresponding sums for the spectroscopic binary properties for all 370 entries in the Galactic O Star Catalog. The percentages for each subgroup represent fractions with the unknown "U" status objects excluded from the totals. Finally, the lower section in Table 5 shows the percentages for the presence of any companion (spectroscopic or visual) again excluding the stars with unknown spectroscopic status.

The results from this larger sample tend to confirm the trend found by Mason et al. (1998) that the binary frequency is lower among field and runaway stars than that found in the cluster/association group. The binaries found among the runaway stars tend to be close systems with nearly equal mass components (HD 1337, ι Ori, Y Cyg) and binaries with neutron star companions (HD 14633, HD 15137, X Per, HD 153919). The former groups are predicted to be infrequently ejected in close gravitational encounters (Leonard & Duncan 1990) while the latter are the result of a supernova explosion in a binary, so both processes must contribute to the ejection of massive stars from clusters. A number of runaways have visual companions that must be optical, chance alignments, since the ejection processes are too energetic for soft, wide binaries to survive.

The binary statistics for the cluster and association group offer us the best estimate of the binary properties at birth (before dynamical and stellar evolution processes alter the statistics). Our results indicate that most O-stars (and by extension most massive stars) are born in binary or multiple star systems. This result is especially striking since those binaries with orbital periods too long for easy spectroscopic detection and too short for direct angular resolution are absent from the totals, so the fractions reported here are clearly lower limits for the binary frequency. Thus, the processes that lead to the formation of massive stars strongly favor the production of binary and multiple star systems.

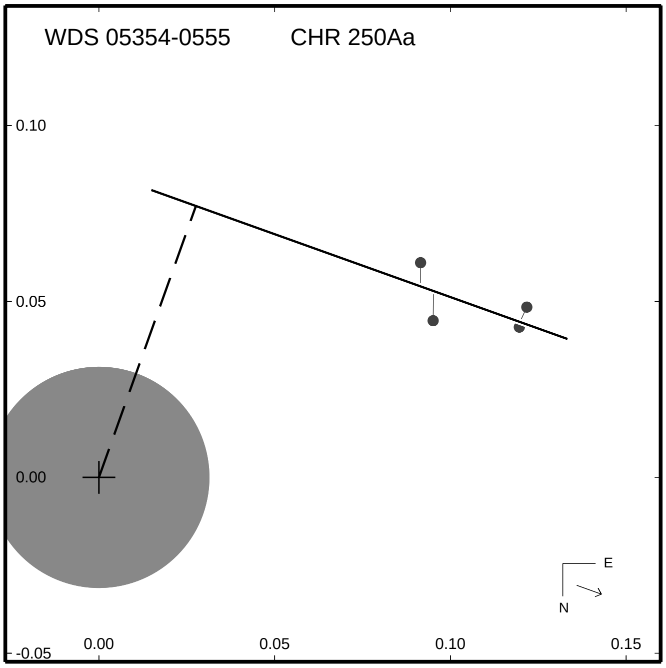

Figure 2. Relative motion of the components of CHR 250 = ι Ori. The straight line is a rectilinear fit to the four measures (two from Mason et al. 1998 and two from Table 2), indicating motion to the ENE. The shaded circle indicates the ~30 mas resolution limit of a 4 m telescope, while the dashed line indicates the closest separation of the two stars assuming their relative motion is rectilinear. The stars appear to have reached a closest separation of 82 ± 5 mas in 1969.7. Of course, the entire time span of observations of this pair is only about 11.5 years; we may instead be observing only a small arc of a long-period orbit.

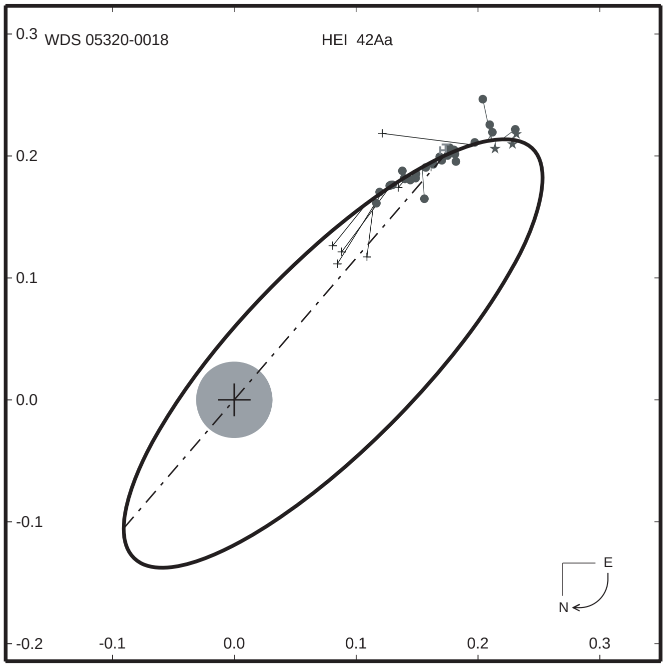

Figure 3. Preliminary orbit for δ Ori. The figure shows the relative motion of the secondary about the primary (indicated by a large "plus" sign); the x and y scales are in arcseconds. The solid curve represents the new orbit determination. The dot-dashed line indicates the line of nodes. The three measures from Table 2 are shown as filled stars and all other high-resolution measurements as filled circles. Micrometer measures are indicated by small plus signs. All measurements are connected to their predicted positions on the orbit by "$O-C$" lines. The direction of motion is indicated on the northeast orientation in the lower right of the plot. The gray filled circle centered on the primary represents that region where the pair is too close to be resolved by speckle interferometry with a 4 m telescope.

5. INDIVIDUAL SYSTEMS

5.1. ι Ori = CHR 250

The complex dynamical relationship of AE Aur, μ Col, and ι Ori is one of the best examples of a binary–binary collision (Gies & Bolton 1986; Leonard & Duncan 1990; Leonard 1995; Clarke & Pringle 1992). As ι Ori is a known close pair (P = 29.13376 d; Marchenko et al. 2000), the much wider speckle component would be hierarchical if physical, with an estimated period of at least 40 y (Gualandris et al. 2004). As the high energy needed to eject AE Aur and μ Col with their runaway velocities seemed inconsistent with the less energetic dynamical interaction required for the CHR 250 pair to remain bound, Gualandris et al. (2004) postulated that this pair was nonphysical, despite their close proximity. Figure 2 shows a least-squares, linear fit (see Hartkopf et al. 2006) to the published data (Mason et al. 1998 and Table 2). The data are also consistent with a long-period orbit, but much longer than ≈ 40 yr.

5.2. δ Ori = HEI 42

We present a first orbit for the wide component of this triple system that is based on all available published data and the new measures listed in Table 2. The previous measurements were extracted from the WDS (Mason et al. 2001) and were weighted following the precepts of Hartkopf et al. (2001a). The orbital elements were determined with an iterative three-dimensional grid-search algorithm (Seymour et al. 2002). The seven orbital elements are presented in Table 6: P (period, in years), a (semimajor axis, in arcseconds), i (inclination, in degrees), Ω (longitude of the node, equinox 2000, in degrees), T (epoch of periastron passage, in fractional Besselian year), e (eccentricity), and ω (longitude of periastron, in degrees). An ephemeris for the period 2010–2018, in two-year increments, is provided in Table B2. The orbit is illustrated in Figure 3.

Table 6
Orbital Elements for δ Ori = HEI 42

Element	Value
P (y)	201
a ($''$)	0.26
i (deg)	108
Ω (deg)	139
T (BY)	1957
e	0.56
ω (deg)	236

Due to the preliminary nature and incomplete phase coverage of the orbital fit, the errors are large and difficult to quantify. It is entirely possible that the companion may continue moving to the southeast for longer than the orbit plot and ephemeris would indicate. The orbit here then may prove wildly erroneous, however, it does serve to highlight the need for periodic monitoring of the pair to verify the orbit predictions. The preliminary orbit indicates a total mass of 32 $M_\odot$ for a distance of 414 pc (Menten et al. 2007).

The A component is itself a close binary with an orbital period of about 5.7 days (see Harvin et al. 2002 for a thorough analysis of the close pair). Curiously, the preliminary orbital period, 201 yr, is close to the derived apsidal period of the close binary (227 ± 37 yr, Monet 1980; 225 ± 27 yr, Harvey et al. 1987).

Table 7
Orbital Elements for δ Sco = LAB 3

Element	Bedding (1993)	Hartkopf et al. (1996)	Miroshnichenko et al. (2001)	This Work
P (y)	10.5	10.583 ± 0.075	10.58[a]	10.68 ± 0.05
a ($''$)	0.11	0.1067 ± 0.0067	0.107[a]	0.104 ± 0.006
i (deg)	70	48.5 ± 6.6	38 ± 5	39 ± 8
Ω (deg)	0	159.3 ± 7.6	175	153 ± 9
T (BY)	1979.3	1979.41 ± 0.14	2000.693 ± 0.008	2000.693[b]
e	0.82	0.92 ± 0.02	0.94 ± 0.01	0.94[b]
ω (deg)	170	24 ± 13	-1 ± 5	29 ± 12

Notes.
[a] Parameter adopted from Hartkopf et al. (1996) solution.
[b] Parameter adopted from Miroshnichenko et al. (2001) solution.

5.3. *δ Sco = LAB 3*

Bedding (1993) published the first set of orbital elements for δ Sco, followed a few years later by an updated solution from Hartkopf et al. (1996). Both solutions were based solely on interferometric data (speckle interferometry plus two measures made using aperture masking). Miroshnichenko et al. (2001) obtained complementary radial velocity data which tied down T quite precisely and also gave a more accurate estimate of the eccentricity, while adopting the values for period and semimajor axis obtained by Hartkopf et al. (1996).

Since the 1996 solution, observations have covered over one additional revolution. Published data include a speckle measure by Horch et al. (1999) and one measure by *Hipparcos* (ESA 1997). This paper includes new speckle measures from the Kitt Peak and Cerro Tololo 4 m telescopes, the Mount Wilson 100 inch, and the USNO (Flagstaff Station) 61 inch, as well as unpublished KPNO and CTIO 4 m observations made with the CHARA speckle camera. A new orbital solution was determined, utilizing all available interferometric data and adopting the T and eccentricity values of Miroshnichenko et al. (2001). Elements from this new orbit as well as the previously published solutions are given in Table 7; future ephemerides for the new orbit are given in Table B2. The new solution and all data used in its determination are shown in Figure 4. Here speckle data from this paper (Table 2) are shown as filled stars, while other interferometry measures are indicated by filled circles; the *Hipparcos* measure is shown as a letter “H.” Measures are connected to their predicted locations along the orbit by “$O-C$” lines; the dotted lines indicate measures given zero weight in the final orbital solution. The dot-dashed line indicates the line of nodes and the shaded circle surrounding the origin indicates the Rayleigh separation limit for a 4 m telescope. At two epochs in early 1990, observations obtained with the KPNO and CTIO 4 m telescopes did not resolve the pair; these are indicated by dotted $O-C$ lines from the origin to their predicted locations along the orbit. According to the orbital solution, these observations should have been marginally resolved. However, given a magnitude difference $\Delta m > 2$ mag, the lack of resolution so close to the Rayleigh limit is not at all surprising. The total mass of the system is approximately 27 $M_\odot$ for a distance of 140 pc (Shatsky & Tokovinin 2002).

5.4. *Notes on Stars Listed in Table 1*

HD 68243 = WSI 55Ba,Bb. This star, γ^1 Vel, is the B component of a group of stars surrounding the bright WR star, γ^2 Vel (which is a spectroscopic binary that has been resolved by optical long baseline interferometry; North et al. 2007).

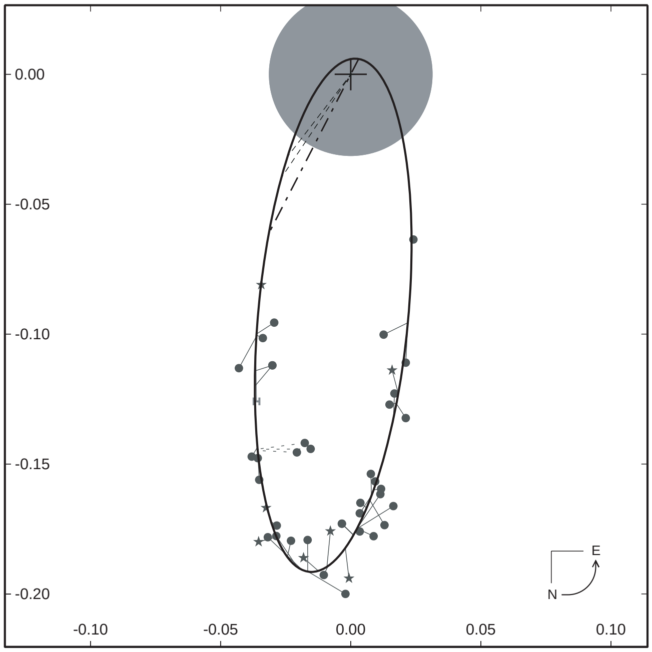

Figure 4. New orbit for δ Sco as described in Section 5.3. The symbols have the same meaning as in Figure 3.

CPD–59 2636 = WSI 56. A spectroscopic study by Albacete Colombo et al. (2002) detected three spectral components. The brighter star we observed probably corresponds to their identification of an A (O7 V) + B (O8 V) spectroscopic binary with a period of 3.6 d while the fainter star is probably their component C (O9 V), itself a single-lined spectroscopic binary with a period of 5.05 d. Thus, this is a quadruple system.

HD 114737 = WSI 57. Not detected by Mason et al. (1998), it is unclear whether the lack of detection earlier was due to the faintness of the companion ($\Delta m = 1.5$) or to a smaller separation at that time.

HD 114886 = WSI 58Aa,Ab. Like HD 114737 above, it is unclear whether the lack of detection earlier was due to a magnitude ($\Delta m = 1.6$) or separation issue.

HD 124314 = WSI 59Ba,Bb. This is a close pair associated with the B component of the wider known pair COO 167.

HD 319703B = WSI 61Ba,Bb. This is the first measurement of a close companion to the B component of the AB pair (separated

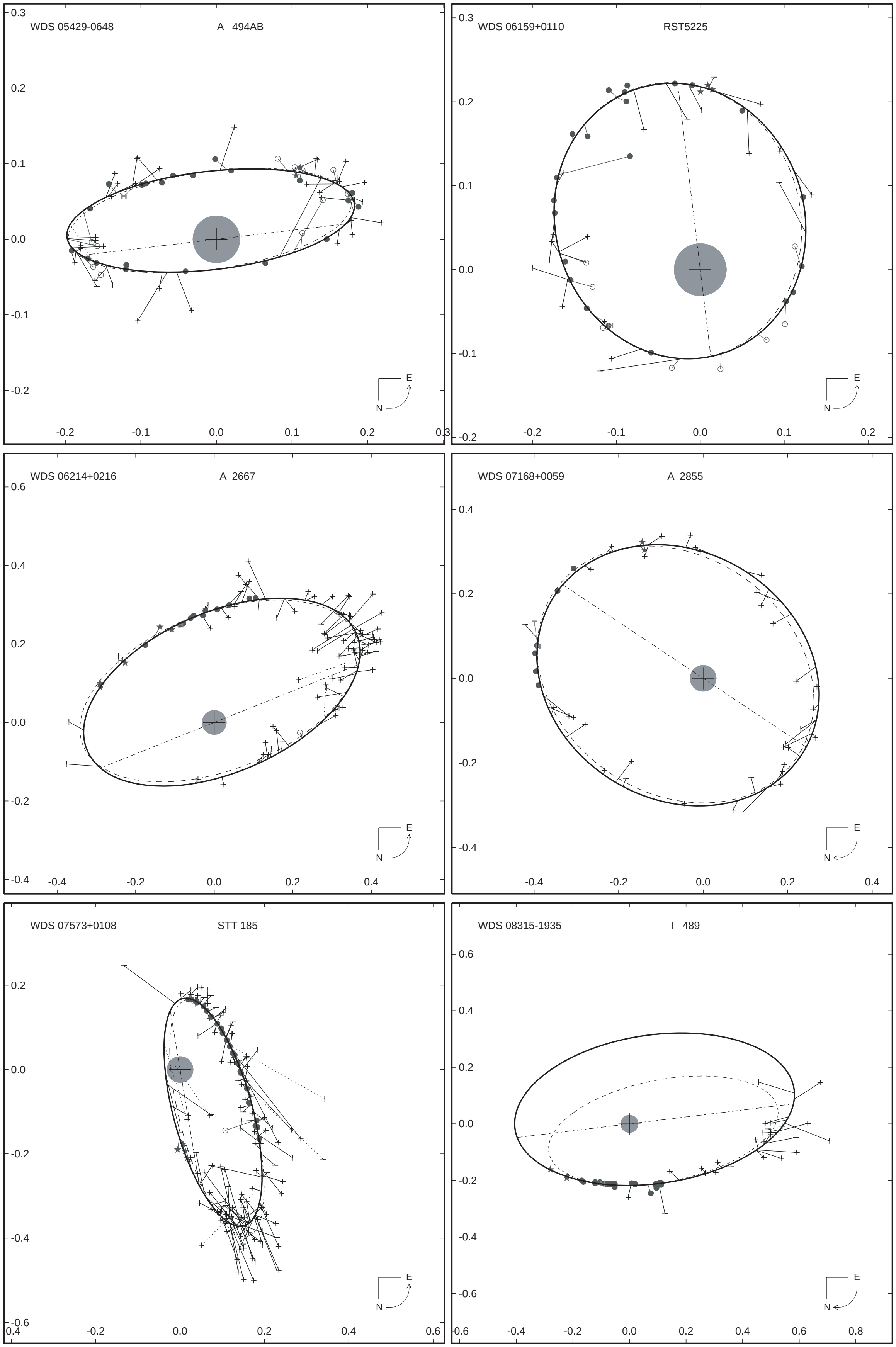

Figure 5. New orbits for the systems listed in Table B1 together with the most recent published elements for these systems and all published data in the WDS database. See the text and Figure 3 for a description of symbols used in this and in Figure 6.

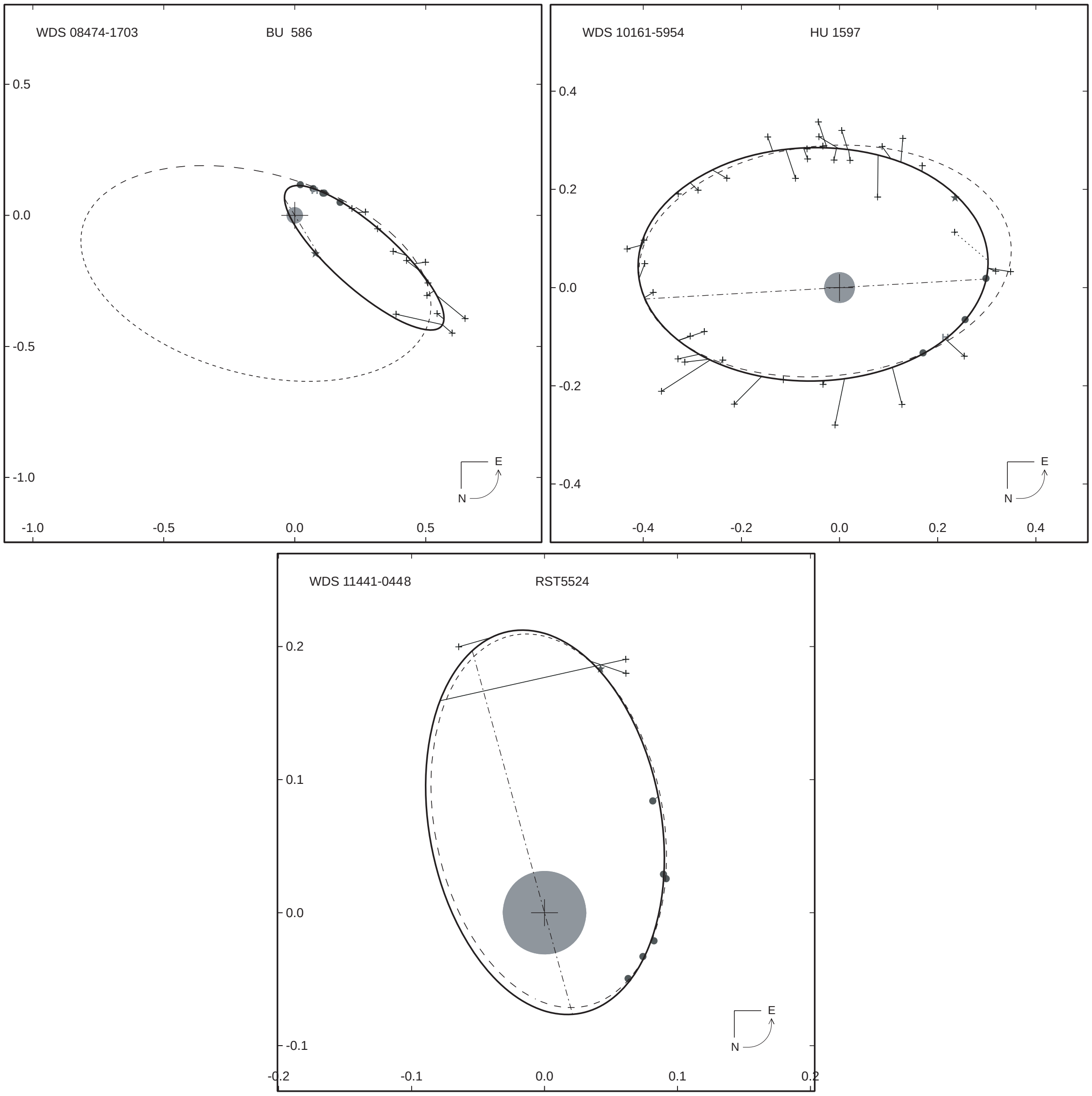

Figure 6. New orbits (continued).

by 14″.5). Unfortunately, the A component (also an O-star) was not observed.

HD 319718C = WSI 62CD and CE. Two additional components were resolved while observing the known BC pair. They can also be seen in an *HST* image made by Maíz-Apellániz et al. (2007) near star B = Pismis 24-17. Unfortunately, we did not observe the A component = Pismis 24-1 that is also a resolved binary (Maíz-Apellániz et al. 2007).

Cyg OB2-22 = Schulte 22 = WSI 66. Our measurements agree with the first results on the pair from Walborn et al. (2002), who determined O-type classifications for both components.

5.5. *Notes on Stars Listed in Table 2*

HD 47839 = CHR 168Aa,Ab = 15 Mon. The earlier 15 Mon orbits (Gies et al. 1993, 1997) are both poor fits to the data listed in Table 2 as well as other unpublished data from the *HST* FGS and optical long baseline interferometry. All these data are being collated for a new combined solution orbit determination (D. R. Gies et al. 2009, in preparation) .

HD 97950 = B 1184 AB-F. This multiple star is actually the core of the distant and massive star cluster NGC 3603 (see Figure 1 in Drissen et al. 1995). Drissen et al. (1995) identify three WR stars and 11 O-stars in the core region.

HD 193322 = CHR 96Aa,Ab. The multiple system HD 193322 was first split by speckle interferometry in 1985 (McAlister et al. 1987) and regularly resolved until closing within the resolution limit of a 4 m telescope (30 mas) in 1989. The preliminary 31-year orbit (Hartkopf et al. 1993) had very small residuals but undersampled phase space (covering only 9% of the orbit). Subsequent to this, the A component was recognized as a close 311 d spectroscopic binary (McKibben et al. 1998). In addition to the speckle resolution listed in Table 2, separated fringe packet solutions with the CHARA Array have been obtained several times since 2005. The "B" component can act as a calibrator in the field of view to allow for rapid data acquisition and reduction for a baseline visibility plus spectroscopy combined solution of the inner pair. A preliminary version was recently presented (Turner et al. 2008a) and a complete analysis of the multiple system is underway (T. ten Brummelaar et al.

Table A1
Speckle Interferometric Measurements of Double Stars

WDS Designation $\alpha\delta$ (2000)	Discoverer Designation			Epoch (BY-2000)	θ (deg)	ρ (″)	n	$[O-C]_\theta$ (deg)	$[O-C]_\rho$ (″)	Reference	Notes
00121+5337	BU	1026	AB	5.8625	308.1	0.319	1	−0.1	−0.005	Hartkopf et al. (1996)	a
				7.5885	308.5	0.326	1	−2.0	−0.005	Hartkopf et al. (1996)	a
00167+3629	STT	4		5.8615	110.1	0.247	2	−5.8	−0.010	Alzner (2000)	
00206+1219	BU	1015		5.8601	98.7	0.465	2	−4.3	0.015	Scardia et al. (2000)	a
				7.6019	100.8	0.473	1	−4.1	0.016	Scardia et al. (2000)	a
00550+2338	STF	73	AB	5.8616	316.6	0.983	2	−1.2	−0.016	Docobo & Costa (1990)	a
				7.6021	318.4	1.010	1	−1.8	−0.016	Docobo & Costa (1990)	a
01017+2518	HDS	134		5.8627	339.7	0.106	1	−0.3	0.012	Balega et al. (2006)	
01024+0504	HDS	135		5.8574	119.5	0.379	1	0.0	0.002	Balega et al. (2006)	
01072+3839	A	1516	AB	5.8615	318.8	0.128	2	4.7	−0.007	Hartkopf et al. (2000)	a
				7.6049	334.4	0.130	1	5.2	−0.009	Hartkopf et al. (2000)	a
01108+6747	HDS	155		5.8625	167.9	0.122	1	−1.9	−0.010	Balega et al. (2006)	a
				7.6049	184.4	0.114	1	−2.1	0.003	Balega et al. (2006)	a
01198−0031	STF	113	AB	5.8656	16.7	1.650	1				
	FIN	337	BC	5.8656	3.3	0.127	1	15.9	0.002	Mason & Hartkopf (1999)	1
01243−0655	BU	1163		5.8656	232.1	0.114	1	0.8	0.003	Söderhjelm (1999)	a

Notes. (a) System used in characterizing errors or investigating detection space. (1) Orbit in need of correction. (2) Not measured before (Table 1). (3) Pleiades cluster member (Mason et al. 1993a). (4) Also known as HD 23608. Estimated $\Delta m = 0.6$. (5) Pair observed to investigate properties of multiple systems. (6) Hyades cluster member (Mason et al. 1993b). (7) Also known as HD 28305. Estimated $\Delta m = 2.4$. (8) While the 6th Orbit Catalog lists two possible solutions for this pair, the measurement fits better the second orbit listed here. (9) Spectroscopic analysis of this pair in progress. (10) Quadrant flip necessary for this orbit. (11) Confirming observation. (12) Multiple possible orbits for this pair, none of which fit well. While correction may be necessary, the data coverage may be insufficient. (13) While the 6th Orbit Catalog lists two possible solutions for this pair, the measurement fits better the second orbit listed here. Quadrant flip necessary for the second orbit. (14) Also known as P 434. Estimated $\Delta m = 1.5$. (15) Also known as P 434. Estimated $\Delta m = 2.5$. (16) Also known as P 456. Estimated $\Delta m = 2.5$. (17) Eclipsing SB2 with third light indicated.

(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.)

2009, in preparation) as is determination of the distance to the surrounding cluster, Collinder 419 (L. C., Jr., Roberts et al. 2009, in preparation).

BD+40 4212 = ES 1679. The separation of this binary has declined from $\rho = 4.''5$ in 1917 (Espin 1918) to $\rho = 3.''5$ in 2005.

WR 146 = NML 1. Our measurement of this faint pair ($V_{a,b} = 16.2, 16.4$) confirms the discovery observation of Niemela et al. (1998).

WR 147 = NML 2. The very faint secondary ($V_{a,b} = 15.0, 17.2$) is at the very limit of the USNO speckle camera. This pair was also first resolved by Niemela et al. (1998). Like NML 1 above, this pair was not detected in the earlier WR speckle survey of Hartkopf et al. (1999) due to the limitations of the camera used at that time.

5.6. *Notes on Stars Listed in Table 3*

HD 103006 = TDS 8073. The *Tycho* satellite (Fabricius et al. 2002) resolved this pair at 0.″50 in 1991, but the observation remains unconfirmed.

HD 106508 = FIN 195. Finsen (1951) resolved this pair at 0.″40 in 1928, and it was measured at 0.″34 in 1934 (Rossiter 1955) and 1941 (van den Bos 1956), and at 0.″178 in 1991 (ESA 1997), the only other published observation in the last 67 years. Possibly the pair closed to <0.″03 at the time of this observation.

HD 138923 = FIN 231. Finsen (1934) resolved this pair in 1929 at a separation of 0.″18 and followed it over 30 years as it closed to 0.″11 in 1954 and <0.″119 in 1959 (Finsen 1953, 1954, 1960). No published measurements have been made in over 50 years, other than one unresolved *Hipparcos* observation in 1991 (ESA 1997); this suggests the pair may have closed to <0.″03 at the time of this observation.

HD 152386 = CHR 253. This object was resolved in 1996 into a 0.″55 pair (Mason et al. 1998), but the discovery is unconfirmed.

HD 168878 = CHR 235. This occultation pair (Africano et al. 1978) was resolved by speckle into a 0.″13 pair in 1996 (Mason et al. 1996); however, this discovery has never been confirmed.

HD 173524 = ISO 7Aa,Ab. Isobe et al. (1990) and Isobe (1991) resolved this 0.″20 pair in 1987; however, this discovery has never been confirmed, with nine other unresolved observations published to date (Hartkopf et al. 2001b).

HD 200595 = BU 1138. This pair has gradually closed from 0.″3 in 1888 (Hough 1890) to 0.″07 in 2001 (Table 2); apparently it closed to <0.″03 at the time of the observation listed in Table 3.

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Table A2
Null Companion Detection[a]

R.A., Decl. (2000) (hhmmss.ss±ddmmss.s)	Cluster, Other Designation	HD, HIP, Other Designation	Date (BY)	Telescope Code	Notes
005319.51+040510.7	** A 2307	HD 5143	2005.8627	K	1
010704.52−003531.3	** HDS 144AB	HD 6639	2005.8656	K	2
011343.80+073431.8	** STF 10A	HD 7344	2005.8627	K	
014458.89+270247.6	** COU 750	BD+26287	2005.8627	K	3
020348.12−002024.5	** TOK 38Aa,Ab	HD 12641	2005.8656	K	4
024221.92+200041.7	** BLA 1Aa,Ab	HD 16811	2005.8627	K	4
025805.08+204007.7	Melotte 25 vB 154	HD 18404	2005.8627	K	h
031712.20+452222.0	GJ 3213	G 078−028	2005.8684	K	5
032732.46+255400.2	Melotte 22 AK III-31	BD+25547	2005.8629	K	p
033204.86+434012.6	** COU1688	HD 21727	2005.8629	K	6

Notes. Telescope code—C: CTIO 4 m; K: KPNO 4 m. (1) The Seymour & Hartkopf (1999) orbit predicts a separation of about $0\farcs07$ at the time of this observation; this orbit was based on data only through 1995, however, so the pair may have closed more than predicted. (2) The known companion is too faint for detection here. (3) The most recent orbit of this pair (Docobo & Ling 2005b) predicts a separation of $0\farcs28$ at this epoch; it is unknown why the pair was not resolved. (4) Separation of the known close companion may have been $< 0\farcs03$ at the time of this observation. (5) Observed with a Johnson *V* filter and usually a lower magnification microscope objective due to the character of the target. The resolution limit for this observation is estimated at $0\farcs05$. (6) This pair was resolved four times between 1978 and 1986 (separations $0\farcs09$–$0\farcs14$); however, there are also 20 published unresolved observations between 1982 and 2004, including two 6 m speckle observations. (7) Observed one component of a wide double/multiple. (8) The 1991 discovery measure of this pair (Mason et al. 1993a) remains unconfirmed. (9) This object was unresolved in five observations between 1988 and 1993, using techniques including visual and infrared speckle interferometry, the *HST* fine-guidance sensor, and *Hipparcos*. The sole resolved measure (Barstow et al. 2001) was made in 1999 using the *HST* planetary camera in the ultraviolet (197 nm). (10) Patience et al. (1998) resolved this pair twice ($\sim 0\farcs045$) at 2.2 μm on the Palomar 5 m, in 1996 and 1997. Earlier observations (*HST*, visual speckle) were unable to detect a secondary. (11) The known companion has too large a magnitude difference for detection here. (12) Due to its highly inclined orbit, the separation for this pair ranges from $0\farcs3$ to $0\farcs014$ over the course of $\sim$ 12 years. The pair was approaching closest apparent separation at the time of this observation, so presumably $\rho < 0\farcs03$. (13) The AB components of this triple were resolved in 1936 and 1937, but not recovered since then. The AB–C pair has widened to probably $1\farcs5$ at this time; the C component is also too faint to detect with the filter used. (14) First resolved by Rossiter (1955) in 1939 at $0\farcs20$, the pair was confirmed by Holden (1972) in 1970 at $0\farcs18$ (with a large change in position angle), but unresolved by *Hipparcos* in 1991 (ESA 1997). There have been no other published observations. Perhaps orbital motion has brought the pair closer than $\rho < 0\farcs03$ at the time of this observation. (15) This occultation pair was marginally resolved twice in 1984 (Mason 1996); all subsequent attempts to resolve this occultation pair have been unsuccessful. (16) This occultation pair was resolved once in 1980 at $0\farcs365$ (McAlister et al. 1983); this discovery remains unconfirmed, however, despite 13 published attempts. (17) The A component of a $5''$ pair is a spectroscopic triple and an irregular variable (d Ser). The pair was initially resolved in 1951 by eyepiece interferometry (Wilson 1952) at a separation of $0\farcs06$. McAlister & Hendry (1982) also resolved it in 1976, although at a very different separation ($0\farcs25$) and angle. Some 10 unresolved observations have been published since 1976, suggesting that the earlier resolutions may instead have been artifacts. (18) This pair has closed steadily in recent years, from $0\farcs21$ in 1991 to $0\farcs08$ in 2001. It may perhaps have been closer than 0\farcs 03 at the time of this observation. (19) Only six observations have been published, all between 1976 and 1989; separations have ranged from $0\farcs16$ to $0\farcs045$, as well as two unresolved observations. No clear pattern of motion has yet been discerned. (20) This pair was resolved several times between 1936 and 1954 ($\rho \sim 0\farcs09$–$0\farcs14$), unresolved several times between 1959 and 1964, resolved once in 1989 (0\farcs 13), and unresolved by *Hipparcos* in 1991. No observations have been published since that time. (21) The most recent published orbit (Mason & Hartkopf 1999) predicts a separation of about $0\farcs054$ at this time of this observation, decreasing to $0\farcs005$ by 2006.87. Periastron may have occurred slightly earlier than predicted. (22) Only three observations of this pair have been published, indicating fair orbital motion and a decrease in separation from 67 to 50 mas between 1985 and 1991. The pair therefore may well have been $< 0\farcs03$ in 2005. However, the wider MCA 60AB pair remained nearly stationary at ($\sim 145^\circ, 0\farcs25$) between 1980 and 1998; it is unknown why this pair was not resolved. (23) This pair was measured some 34 times between 1975 and 1999, usually in the 50–70 mas range of separation. No observations have been published since 1999, however. Published orbits by McAlister (1980) and Pourbaix (2000) both give periods of about 2.25 yr and predict separations at the time of this observation of $0\farcs036$ and $0\farcs044$, respectively. Periastron separations for both orbits are about $0\farcs01$. (24) Recent orbital solutions (Tokovinin 1986; Pourbaix 2000) predict a separation of about $0\farcs052$ for 2005.86; it is unknown why the pair was not resolved here. (25) Both the Aa,Ab and Aa,Ac pairs should have separations of $\sim 0\farcs25$; it is unknown why neither pair was resolved here. (h) Hyades cluster member (Mason et al. 1993b). (o) New Horizon's occultation star. (p) Pleiades cluster member (Mason et al. 1993a).

[a] $\rho < 0\farcs03$ except as noted.

(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 A

OTHER SYSTEMS OBSERVED

Tables A1 and A2 are identical in form to Tables 2 and 3, respectively, but the targets listed here are selected from other sample sets as indicated in the more extensive collection of notes. As many of these systems were used for either primary (CTIO) or secondary (KPNO) scale and angle calibration, many have calculated orbits, with residuals derived from orbital solutions given in Table B1.

APPENDIX B

CORRECTED ORBITS

We found that some of those pairs identified as calibration systems in Table A1 (used to investigate differential magnitude detection rates at various separations; Figure 1) had poorly defined orbits. The KPNO measures, independently calibrated by use of the slit-mask, allowed us to optimize these orbits and to generate ephemerides, which helped us calibrate the CTIO measures. Going one step further, these CTIO measures could

Table B1
New Orbital Elements

WDS (Figure No.)	Discoverer Designation			P (yr)	a (″)	i (deg)	Ω (deg)	T (yr)	e	ω (deg)	Grade	Published Orbit Reference
05429−0648	A	494	AB	20.13	0.208	71.7	96.8	1959.03	0.392	273.2	2	Mason & Hartkopf (1999)
(4a)				±0.02	±0.001	±0.3	±0.4	±0.06	±0.003	±1.4		
06159+0110	RST	5225		29.70	0.166	15.6	6.9	1965.51	0.379	16.4	2	Hartkopf & Mason (2001a)
(4b)				±0.13	±0.001	±3.0	±12.4	±0.20	±0.007	±13.5		
06214+0216	A	2667		100.23	0.393	58.5	111.8	1931.40	0.335	249.2	2	Seymour & Mason (2000a)
(4c)				±1.11	±0.004	±0.7	±1.1	±0.91	±0.014	±3.7		
07168+0059	A	2855		64.44	0.349	148.3	56.3	1958.36	0.178	329.2	2	Seymour & Mason (1999)
(4d)				±0.45	±0.003	±2.1	±3.7	±0.69	±0.010	±7.0		
07573+0108	STT	185		58.01	0.343	72.5	9.5	1944.22	0.672	240.7	2	Hartkopf & Mason (2001b)
(4e)				±0.08	±0.002	±0.3	±0.4	±0.13	±0.002	±1.2		
08315−1935	I	489		261.06	0.504	122.1	96.9	2005.97	0.241	141.0	4	Zulevic (1997)
(4f)				±15.48	±0.007	±2.7	±1.7	±7.48	±0.010	±14.6		
08474−1703	BU	586		194.61	0.604	72.5	31.4	2003.08	0.905	239.6	4	Mante (2003b)
(5a)				±10.76	±0.018	±3.2	±2.0	±0.38	±0.014	±4.9		
10161−5954	HU	1597		83.90	0.365	48.8	93.4	1989.02	0.253	303.7	2	Ling & Prieto (1990)
(5b)				±0.65	±0.003	±0.8	±1.0	±0.35	±0.006	±1.4		
11441−0448	RST	5524		56.24	0.148	48.7	15.4	1984.17	0.480	336.9	3	Zirm (2002)
(5c)				±1.92	±0.003	±4.4	±5.1	±0.81	±0.050	±7.7		

Table B2
Orbital Ephemerides

WDS Designation	Discoverer Designation			BY2010.0		BY2012.0		BY2014.0		BY2016.0		BY2018.0	
				θ (deg)	ρ (″)	θ (deg)	ρ (″)	θ (deg)	ρ (″)	θ (deg)	ρ (″)	θ (deg)	ρ (″)
05320−0018	HEI	42	Aa	131.9	0.317	131.3	0.318	130.7	0.319	130.1	0.320	129.5	0.320
05429−0648	A	494	AB	213.1	0.100	244.8	0.145	260.8	0.188	272.6	0.194	289.8	0.120
06159+0110	RST	5225		202.4	0.228	214.0	0.225	226.3	0.214	240.3	0.198	257.4	0.176
06214+0216	A	2667		263.0	0.321	268.2	0.328	273.2	0.333	278.1	0.334	283.1	0.331
07168+0059	A	2855		183.5	0.305	170.4	0.285	155.5	0.270	139.2	0.260	122.2	0.258
07573+0108	STT	185		12.7	0.325	15.4	0.359	17.8	0.381	20.0	0.395	22.0	0.400
08315−1935	I	489		293.8	0.348	290.9	0.359	288.2	0.369	285.6	0.378	283.2	0.385
08474−1703	BU	586		35.6	0.287	37.4	0.334	38.8	0.373	40.0	0.408	41.0	0.438
10161−5954	HU	1597		144.0	0.290	152.8	0.285	161.9	0.281	171.1	0.281	180.3	0.283
11441−0448	RST	5524		175.3	0.203	179.2	0.209	182.8	0.212	186.4	0.213	190.0	0.212
16003−2237	LAB	3		11.3	0.107	334.2	0.075	348.0	0.163	354.0	0.191	359.4	0.182

then be incorporated in a new, improved orbit solution using the same methodology as that described in Section 5.2. These orbital elements are presented in Table B1, together with their grades (see Hartkopf et al. 2001a for a description of the grading scale). Also provided in Table B1 is the reference to the previous "best" published orbit. Formal errors are listed below each element. Future ephemerides are presented in Table B2 and relative orbit plots are illustrated in Figures 5 and 6, with the dashed curve indicating the prior orbit listed in Table B1.

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