THE HIGH ANGULAR RESOLUTION MULTIPlicity OF MASSIVE STARS

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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′′03 and 5′′ with relatively bright companions (ΔV < 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 (ι Ori, δ 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...
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 $\Delta m$, 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 nonlinear (i.e., Keplerian), indicating whether the pair is optical or 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 (Maiz-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.

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 $0''01$ 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 1.45′ for nominal conditions and 3′ 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′ 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 $\mu$ and $\theta$ 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

![Figure 1. Plot of separation ($\rho$) vs. magnitude difference ($\Delta m$) for pairs observed. The separations are direct measurements from Tables 2 and A1 while $\Delta m$ is the tabulated value from WDS (Mason et al. 2001). The curved lines indicate the measure of difficulty relationship of Opik (1924) as modified by Heintz (1978a). The $\rho$-$\Delta m$ combinations below the solid line are considered completely unknown. 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).](image)
Table 1

Newly Resolved Pairs

| Coordinates $\alpha, \delta$ (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 Ir+                | 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     |
| 175531.95−162247.0                | 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. (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 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 Maiz-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 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 $\theta$ (in degrees), and the separation $\rho$ (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 $\Delta\eta$, 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 $\theta$ and $\rho$ 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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Table 2 presents coordinates and magnitude information from CDS 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.

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

2003 all-sky release http://pegasus.phast.umass.edu/.
| WDS Designation | Discoverer | Other Identifier | Epoch (BY) | $\theta$ (deg) | $\rho$ (mag) | $\Delta u$ (deg) | n | $[O-C]_u$ (deg) | $[O-C]_p$ (deg) | Reference | Notes |
|-----------------|------------|-----------------|-----------|----------------|-------------|-----------------|---|-----------------|-----------------|----------|------|
| 02407+6117      | CHR        | Aa,Ab           | HD 16429  | 2005.8628      | 270.7       | 0.277           | 2.7 | 1               |                  |          | 3    |
| 05297+3523      | HU         | HD 35921        | 2005.8634 | 252.9          | 0.608       | 1.2             | 1   |                  |                  |          |      |
| 05320−0018      | HEI        | Aa,Ab           | $\delta$ Ori | 2001.0822      | 133.9       | 0.297           | 1.4 | 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        | Aa,Ab           | HD 37041  | 2005.8662      | 278.9       | 0.392           | 3.2 | 1               |                  |          |      |
| 05354−0555      | CHR        | Aa,Ab           | $\iota$ Ori | 2005.8662      | 111.7       | 0.131           | 2.4 | 1               | 1.4             | 0.003     | Section 5.1 |
| 05387−0236      | BU         | AB              | $\sigma$ Ori | 2005.8662      | 96.9        | 0.254           | 1.2 | 1               | −0.3            | −0.001    | Section 5.1 |
| 06410+0954      | CHR        | Aa,Ab           | 15 Mon    | 2001.0197      | 231.1       | 0.061           | 1.2 | 1               | −110.1          | 0.022     | Turner et al. (2008b) |
| 07187−2457      | FIN        | Aa,Ab           | $\tau$ CMa | 2006.1937      | 125.2       | 0.128           | 0.4 | 1               |                  |          |      |
| 08095−4720      | WSI        | Ba,Bb           | HD 68243  | 2006.1882      | 273.6       | 0.085           | 1.5 | 1               |                  |          | 2, 3, Section 5.4 |
| 08392−4025      | B          | HD 73882        |           | 2006.1884      | 254.4       | 0.662           | 1.3 | 1               |                  |          |      |
| 10440−5933      | NEL        | Aa,Ab           | HD 93129A | 2006.1886      | 10.1        | 0.043           | 0.9 | 1               |                  |          |      |
| 10441−5935      | HJ         | AB              | HD 93161  | 2006.1886      | 115.3       | 1.982           | 0.1 | 1               |                  |          |      |
| 11383−6322      | I          | AB              | HD 101205 | 2006.1967      | 113.8       | 0.357           | 0.3 | 2               |                  |          |      |
| 11406−6234      | CPO        | HD 101545       |           | 2006.1888      | 219.2       | 2.543           | 0.6 | 1               |                  |          |      |
| 13138−6335      | WSI        | HD 114737       |           | 2006.1888      | 235.4       | 0.188           | 1.5 | 1               |                  |          | 2, 3, Section 5.4 |
| 13147−6335      | WSI        | Aa,Ab           | HD 114886 | 2006.1888      | 276.9       | 0.243           | 1.6 | 1               |                  |          | 2, 3, Section 5.4 |
| 14150−6142      | WSI        | Ba,Bb           | HD 124314B| 2006.1891      | 245.8       | 0.208           | 1.3 | 1               |                  |          | 2, 3, Section 5.4 |
| 16466−4705      | B          | AB              | HD 150958 | 2006.1919      | 245.1       | 0.297           | 1.7 | 1               |                  |          |      |
| 16540−4148      | B          | AB              | HD 152234 | 2006.1945      | 75.3        | 0.513           | 2.3 | 1               |                  |          |      |
| 16542−4150      | CHR        | Aa,Ab           | HD 152248 | 2006.1945      | 236.5       | 0.052           | 2.0 | 1               |                  |          |      |
| 1663−4040       | HDS        | HD 152623       |           | 2006.2000      | 307.4       | 0.238           | 1.3 | 1               |                  |          |      |
| 16659−4031      | CHR        | Aa,Ab           | HD 152723 | 2006.2000      | 125.6       | 0.098           | 1.7 | 1               |                  |          | 3, 4 |
| 17158−3344      | SEE        | HD 155889       |           | 2006.1945      | 282.2       | 0.189           | 0.6 | 1               | −0.7            | 0.005     | Turner et al. (2008b) |
| 18152−2023      | CHR        | Aa,Ab           | HD 167263 | 2006.1946      | 149.7       | 0.069           | 2.0 | 1               |                  |          | 3    |
| 20074+3543      | STT        | AB              | HD 191201 | 2005.8679      | 82.4        | 0.971           | 1.8 | 1               |                  |          |      |
| 20181+4044      | CHR        | Aa,Ab           | HD 193322 | 2005.8652      | 100.4       | 0.086           | 1.2 | 1               | −5.6            | 0.019     | Hartkopf et al. (1993) |
|                 |            |                 |           | 2007.6042      | 100.8       | 0.067           | 1   | −14.3           | 0.005           | Hartkopf et al. (1993) |
|                 |            |                 |           | 2008.4508      | 116.7       | 0.066           | 1   | −3.2            | 0.005           | Hartkopf et al. (1993) |
|                 | STF        | AB              |           | 2001.4991      | 245.7       | 2.713           | 1.3 | 1               |                  |          |      |
| 20189+3817      | A          | AB              | HD 193443 | 2005.8652      | 258.7       | 0.126           | 0.3 | 1               |                  |          |      |
| 21390+5729      | MIU        | Aa,Ab           | HD 206267 | 2005.8654      | 247.9       | 0.118           | 1.1 | 1               |                  |          | 3    |

Table 2

Speckle Interferometric Measurements of Double Stars
| WDS Designation | Discoverer Designation | Other Identifier | Epoch (BY) | $\theta$ (deg) | $\rho$ ("') | $\Delta n$ (mag) | $|O - C|_{\theta}$ (deg) | $|O - C|_{\rho}$ ("') | Reference | Notes |
|-----------------|------------------------|------------------|------------|---------------|-------------|----------------|------------------------|----------------|-----------|-------|
| 02512+6023      | BU 1316 AB             | HD 17520         | 2005.8620  | 297.8         | 0.309       | 0.5          | 2                     |                |           |       |
| 05228+3325      | BU 887 AB              | BD+331026        | 2008.8635  | 195.1         | 1.089       | 0.8          | 1                     |                |           |       |
| 07523−2626      | WSI 54                 | HD64315          | 2006.1937  | 231.8         | 0.091       | 0.2          | 1                     |                |           |       |
| 10452−5944      | WSI 56                 | CPD−592636       | 2006.1886  | 59.8          | 0.269       | 0.6          | 1                     |                |           |       |
| 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−381748        | 2006.1971  | 333.1         | 1.325       | 1.2          | 1                     |                |           |       |
| 17198−3606      | WSI 61 Ba, Bb         | HD 319703         | 2006.1971  | 15.8          | 0.188       | 1.5          | 1                     |                | 2, 3, Section 5.4 |
| 17247−3412      | DAW 216 BC             | HD 319718         | 2006.1971  | 319.8         | 4.722       | 1.4          | 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 |
| 15150−5951      | HJ 3716 AE             | HD 319718C       | 2006.1971  | 182.0         | 3.628       | 2.8          | 1                     |                | 2         |
| 20358+4123      | NML 1 WR146           | 2001.4993        | 16.8       | 0.157         | 0.4          | 1             | 1                     |                |           |       |
| 20367+4021      | NML 2 WR147           | 2001.4991        | 350.7      | 0.627         | 2.2          | 1             | 1                     |                |           | Section 5.5 |
| 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) |
| 00318+5431      | STT 12 HD 2772        | 2007.6021        | 203.2      | 0.286         | 0.3          | 1             | −2                   | 0.077         | Ling et al. (2005) |
| 00507+6415      | MCA 2 HD 4775         | 2007.6021        | 174.5      | 0.053         | 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) |

### New Sample O-Stars

### Wolf-Rayet Pairs

### B Stars
| WDS Designation | Discoverer | Other Identifier | Epoch (BY) | $\theta$ (deg) | $\rho$ (") | $\Delta m$ | $n$ | $[O - C]_0$ (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) |
| 02145+6631      | MCA        | 6 HD 13474       | 2007.6021  | 99.3           | 0.299       | 1          | −2.2 | −0.015           | Docobo & Ling (2007a) |
| 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   |                 | HD 8610    | 2005.8610      | 313.3       | 1.554      | 0.3  | 2                |                  |          |       |
| 03082+4057      | LAB 2      | Aa,Ab $\beta$ 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 20236   | 2007.6022  | 43.7           | 0.132       | 1.2        | 1    | −6.9             | −0.012           | Romero (2007) |
| 03272+0944      | HDS 433    |                 | HD 21364   | 2005.8616      | 53.8        | 0.224      | 3.8  | 2                |                  | Baize (1994) |
| 03284+6015      | A 980 AB   | HD 21203         | 2007.6022  | 337.9          | 0.364       | 1.6        | 1    | −2.9             | 0.003            | Olicvic & Cveticovic (2005b) |
| 04422+2257      | MCA 16     | Aa,Ab $\tau$ Tau | 2005.8690  | 39.2           | 0.314       | 2.4        | 1    | 1.2              | 0.023            | Olicvic & Cveticovic (2005b) |
| 05145—0812      | BU 555 BC  | HD 34085         | 2005.8662  | 29.8           | 0.124       | 0.1        | 1    |                  |                  |          |       |
| 05245—0224      | MCA 18     | Aa,Ab $\eta$ Ori | 2006.1908  | 302.8          | 0.066       | 1.3        | 1    | −2.1             | 0.005            | Olicvic & Jovanovic (1998) |
| 05245—0224      | DA 5       | AB               | 2005.8662  | 77.4           | 1.715       | 1.3        | 1    |                  |                  |          |       |
| 05272+1758      | MCA 19     | Aa,Ab            | HD 35671   | 2005.8635      | 88.5        | 0.104      | 1.0  | 1                | −20.1            | 0.030    | Olicvic & Jovanovic (1997) |
| 05308+0557      | STF 728    | HD 36267         | 2001.0197  | 46.3           | 1.146       | 1.3        | 1    | −1.5             | 0.000            | Mason (1997) |
| 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) |
| 07143—2621      | FIN 323    | HD 56014         | 2006.1937  | 153.4          | 0.115       | 0.5        | 1    | 2.1              | −0.089           | Olicvic & Cveticovic (2004) |
| 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    |                  |                  |          |       |
| 08328—4153      | RST 4888   | AB               | 2006.1884  | 104.9          | 0.514       | 0.2        | 1    |                  |                  |          |       |
| 08380—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    |                  |                  |          |       |
| 09125—4337      | FIN 317    | Aa,Ab HD 79416   | 2006.1884  | 102.3          | 0.123       | 0.5        | 1    |                  |                  |          |       |
| 09128—6055      | HDG 207    | AB HD 79699      | 2006.1939  | 79.7           | 0.164       | 0.3        | 2    | −16.7            | 0.031            | Heintz (1996a) |
| 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) |
| 11210—5429      | I 879      | $\pi$ Cen       | 2006.1887  | 158.7          | 0.215       | 1.6        | 1    | −1.8             | 0.001            | Mason et al. (1999) |
| 11248—6708      | HDS 1623   | HD 99317         | 2006.1995  | 112.1          | 0.168       | 0.8        | 1    |                  |                  |          |       |
| 11286—4508      | I 885      | HD 99804         | 2006.1887  | 152.8          | 0.647       | 0.4        | 2    | 5.0              | 0.086            | Seymour et al. (2002) |
Table 2
(Continued)

| WDS Designation | Discoverer Designation | Other Identifier | Epoch (BY) | θ (deg) | ρ (") | Δμ (mag) | n | [O − C],ρ (deg) | [O − C],ρ (") | 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 a.a,Ab i Lib   | 2006.1918        | 11.9       | 0.154   | 0.4     | 1 | −0.9          | −0.006         | Mason et al. (1999)| a |
| 15234−5919      | HJ 4757 γ Cir         | 2006.1892        | 5.2        | 0.808   | 0.8     | 2 | 13.6          | 0.001          | Nys (1982)     | 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 δ CrB         | 2008.4849        | 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 i Ser       | 2006.2000        | 262.3      | 0.092   | 0.1     | 1 | −0.1          | −0.003         | Docobo & Ling (2007a)| a |
| 16003−2237      | LAB 3 δ Scl           | 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       | 1                    | −0.6             | −0.003     | Section 5.3 | 7     |
| 2001.5667       | 1                    | −0.6             | −0.004     | Section 5.3 | 7     |
| WDS Designation | Discoverer | Other Identifier | Epoch (BY) | \( \theta \) (deg) | \( \rho \) (") | \( \Delta m \) (mag) | \( n \) | \([O − C]_\rho\) (deg) | \([O − C]_o\) (") | Reference | Notes |
|----------------|------------|------------------|-----------|----------------|--------------|----------------|---|----------------|--------------|----------|-------|
| αδ (2000) | | | | | | | | | | | |
| 16120−1928 | BU | 120 | AB | HD 145502 | 2004.2017 | 348.9 | 0.183 | 1 | −2.0 | 0.003 | Section 5.3 | 9 |
| | MTL | 2 | CD | HD 145502C | 2006.1918 | 354.4 | 0.187 | 1 | −1.8 | −0.005 | Section 5.3 | |
| | LAB | 4 | | σ Her | 2006.5554 | 357.5 | 0.176 | 1 | 0.2 | −0.014 | Section 5.3 | |
| | | | | | 2007.3173 | 359.8 | 0.194 | 1 | 0.5 | 0.012 | Section 5.3 | |
| 16341+4226 | MCA | 48 | Aa,Ab | ρ Her | 2007.6068 | 17.3 | 0.102 | 1 | 0.3 | −0.008 | Brendley & Hartkopf (2007) | |
| 17237+3709 | MCA | 48 | Aa,Ab | ρ Her | 2007.6068 | 32.0 | 0.248 | 1 | 1.8 | −0.019 | Heintz (1996c) | a |
| 17400−0038 | BU | 631 | HD 160438 | 2006.2000 | 89.0 | 0.246 | 0.2 | 1 | 1.8 | −0.019 | Heintz (1996c) | |
| 18003+0422 | WSI | 65 | HD 164284 | 2007.5879 | 155.4 | 0.121 | 1.5 | 1 | | | |
| 18262−1833 | CHR | 236 | HD 169602 | 2007.5880 | 113.1 | 0.143 | 1.5 | 1 | | | |
| 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 | | | |
| 18520+1358 | CHR | 80 | HD 174853 | 2007.5878 | 36.4 | 0.126 | 2.3 | 1 | | | |
| 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 | | | |
| | | | | | 2008.4508 | 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) | |
| | HDS | 3016 | BD+483298 | 2007.6072 | 23.4 | 0.329 | 1.4 | 1 | | | |
| | MCA | 67 | Aa,Ab | HD 202214 | 2005.8654 | 124.5 | 0.045 | 0.6 | 1 | 4.0 | −0.001 | Mante (2002) | |
| | STF | 2780 | AB | HD 202214 | 2005.8654 | 212.4 | 1.021 | 0.3 | 1 | | | |
| | | | | | 2007.5990 | 212.5 | 1.013 | 2 | | | |
| | COU | 2136 | BD+384391 | 2007.6072 | 292.8 | 0.422 | 0.9 | 1 | | | 4 |
Table 2
(Continued)

| WDS Designation | Discoverer Identifier | Epoch (BY) | \( \theta \) (deg) | \( \rho \) (") | \( \Delta m \) (mag) | \( n \) | \([ O - C ]_0\) (deg) | \([ O - C ]_0\) (") | Reference | Notes |
|------------------|-----------------------|------------|-----------------|---------|----------------|------|-----------------|----------------|-----------|-------|
| 21157+4832       | HDS 3024              | BD+473349  | 2007.6072       | 329.6   | 0.283          | 1.9  | 1               |               |           |       |
| 21191+6152       | HDS 3035 Aa,Ab        | HD 203374  | 2007.6073       | 296.5   | 0.294          | 2.3  | 1               |               |           |       |
| 21287+7034       | LAB 6 Aa,Ab \( \beta \) 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               |               |           |       |
| 21340+6029       | HDS 3071              | HD 239700  | 2007.6073       | 291.1   | 0.143          | 1.7  | 1               |               |           |       |
| 21428+6018       | HDS 3093              | HD 239743  | 2007.6073       | 267.3   | 0.140          | 1.6  | 1               |               |           |       |
| 21536−1019       | FIN 358               | HD 208008  | 2007.5992       | 308.3   | 0.130          | 2.0  | 1               | 1.2           | −0.011    | Hartkopf et al. (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) |
|                  |                       |            |                 |         |                |      |                 | −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) \( \Delta m \) 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 non-detection. 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 provides a complete list of single star observations for the massive star sample. The precise coordinate ($\alpha$, $\delta$) 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 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 their birthplaces in stellar clusters and associations) 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 a "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.

Table 3
Null Companion Detection

| R.A., Decl. (2000) | Cluster, Other Designation | V*, ** 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             |       |
| 000603.35+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 1137                   | 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 $\rho < 0.03$. (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 $\rho < 0.03$. (5) The known companion is too faint for detection here. (6) Observed with the USNO g filter ($\lambda_{\text{eff}} = 560$ 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 ($\sim 0.03$). (p) Pleiades cluster member (Mason et al. 1993a).

(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    |
| c Oph | C                   | 1              | Sco OB2     | yes      | 2005ApJ...623L145W     |
| HD 165246 | SBE                | 2              | Sgr OB1     | no       | 2007OEVV...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.)
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).

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.
The stars appear to have reached a closest separation of 82 closest separation of the two stars assuming their relative motion is rectilinear. 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. 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 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.

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 yr (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.

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).
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). 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, \( \gamma^1 \) Vel, is the B component of a group of stars surrounding the bright WR star, \( \gamma^2 \) Vel (which is a spectroscopic binary that has been resolved by optical long baseline interferometry; North et al. 2007).

**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.
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. ...)
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 \( (V_{ab} = 16.2, 16.4) \) confirms the discovery observation of Niemela et al. (1998).

**WR 147 = NML 2.** The very faint secondary \( (V_{ab} = 15.0, 17.2) \) 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 \( \rho = 050' \) in 1991, but the observation remains unresolved.

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

**HD 138923 = FIN 231.** Finsen (1934) resolved this pair in 1929 at a separation of \( \rho = 18' \) and followed it over 30 years as it closed to \( \rho = 11' \) in 1954 and \( \rho = 119' \) 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 \( \rho = 0'03 \) at the time of this observation.

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

**HD 166878 = CHR 235.** This occultation pair (Africano et al. 1978) was resolved by speckle into a \( \rho = 13' \) 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 \( \rho = 20' \) 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 \( \rho = 3' \) in 1888 (Hough 1890) to \( \rho = 0'7 \) in 2001 (Table 2); apparently it closed to \( \rho = 0'03 \) at the time of the observation listed in Table 3.

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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

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.

Table A2
Null Companion Detection\(^a\)

| R.A., Decl. (2000) (hhmmss.ss±ddmmss.ss) | 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                         | ** HD 1441AB                | HD 6639                   | 2005.8656 | K              | 2     |
| 011334.80±073431.8                         | ** STF 10A                  | HD 7344                   | 2005.8627 | K              |       |
| 014458.89±270247.6                         | ** COU 750                  | BD+26287                  | 2005.8656 | K              | 3     |
| 020348.12−002024.5                         | ** TOK 38Aa,Ab              | HD 12641                  | 2005.8656 | K              | 4     |
| 024221.92±200401.7                         | ** BLA 1Aa,Ab               | HD 16811                  | 2005.8627 | K              | 4     |
| 025805.08+240047.7                         | 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                         | ** BD+25287                 | 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 0.07 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 0.28 at this epoch; it is unknown why the pair was not resolved. (4) Separation of the known close companion may have been < 0.03 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 0.05. (6) This pair was resolved four times between 1978 and 1986 (separations 0.09−0.14); 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 (~ 0.045) 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 0.3 to 0.014 over the course of ~ 12 years. The pair was approaching closest apparent separation at the time of this observation, so presumably ρ < 0.03. (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 1.5′′ 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 0.2′′, the pair was confirmed by Holden (1972) in 1970 at 0.18′′ (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 ρ < 0.03 at the time of this observation. (15) This occultation pair was resolved once in 1980 at 0.365′′ (McAlister et al. 1983); this discovery remains unconfirmed, however, despite 13 published attempts. (16) 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 eyepeice interferometry (Wilson 1952) at a separation of 0.06 prime. McAlister & Hendry (1982) also resolved it in 1976, although at a very different separation (0.25′′) 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 Not been observed since 2001. It may perhaps have been closer than 0.15′′ at this time of this observation. (19) Only six observations have been published, all between 1976 and 1989; separations have ranged from 0.16 to 0.045, 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 (ρ ~ 0.09−0.14), unresolved several times between 1959 and 1964, resolved once in 1989 (0.15′′, 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 0.054 at this time of this observation, decreasing to 0.006 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 < 0.03 in 2005. However, the wider MCA 60AB pair remained nearly stationary at (~ 145′′). 0.25′′ 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 period of about 2.25 yr and predict separations at the time of this observation of 0.036 and 0.044, respectively. Periastron separations for both orbits are about 0.01. (24) Recent orbital solutions (Tokovinin 1986; Pourbaix 2000) predict a separation of about 0.052 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 ~ 0.25′′; it is unknown why neither pair was resolved here. (b) Hyades cluster member (Mason et al. 1993b). (o) New Horizon’s occultation star. (p) Pleiades cluster member (Mason et al. 1993a).

\(^a\) ρ < 0.03 except as noted.

(These data appear 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 B

CORRECTED ORBITS

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.
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.

**REFERENCES**

Africano, J. L., Evans, D., Fekel, F., Smith, B., & Morgan, C. 1978, AJ, 83, 1109

Albacete Colombo, J. F., Morrell, N. I., Rauw, G., Corcoran, M. F., Niemela, V. S., & Sana, H. 2002, MNRAS, 336, 1099

Alzner, A. 2000, IAU Comm. 26 Inf. Circ., 141

Alzner, A. 2005, IAU Comm. 26 Inf. Circ., 155

Alzner, A. 2007, IAU Comm. 26 Inf. Circ., 163

Bagnuolo, W. G., Jr., Mason, B. D., Barry, D. J., Hartkopf, W. I., & McAlister, H. A. 1992, AJ, 103, 1399

Baille, P. 1976, A&AS, 26, 177

Baille, P. 1980, IAU Comm. 26 Inf. Circ., 80

Baille, P. 1988, A&AS, 74, 507

Baille, P. 1994, A&AS, 106, 267

Bailea, I. I., Bailea, Y. Y., Hofmann, K.-H., Maksimov, A. F., Pluzhnik, E. A., Schertl, D., Shkikhagoseva, Z. U., & Weigelt, G. 2002, A&A, 385, 87

Bailea, I. I., Bailea, Y. Y., Hofmann, K.-H., Malogolovets, E. V., Schertl, D., Shkikhagoseva, Z. U., & Weigelt, G. 2006, A&A, 448, 703

Barnaby, D., Spiller, E., Christou, J. C., & Drummond, J. D. 2000, AJ, 119, 378

Barstow, M. A., Bond, H. E., Burleigh, M. R., & Holberg, J. B. 2001, MNRAS, 322, 891

Bate, M. R., Bonnell, I. A., & Bromm, V. 2002, MNRAS, 336, 705

Bedding, T. 1993, AJ, 106, 768

Brendley, M., & Hartkopf, W. I. 2007, IAU Comm. 26 Inf. Circ., 163

Brendley, M., & Mason, B. D. 2006, IAU Comm. 26 Inf. Circ., 160

Clarke, C. J., & Pringle, J. E. 1992, MNRAS, 255, 423

Cole, W. A., Fekel, F. C., Hartkopf, W. I., McAlister, H. A., & Tomkin, J. 1992, AJ, 103, 1357

Couture, P. 1984, A&AS, 57, 171

Couture, P. 1997, IAU Comm. 26 Inf. Circ., 131

Couture, P. 1999, in Cat. de 2700 Etoiles Doubles “COU” (Nice: Obs. de la Côte d’Azur)

Cvetkovic, Z. 2006, IAU Comm. 26 Inf. Circ., 160

Cvetkovic, Z. 2008, IAU Comm. 26 Inf. Circ., 164

Cvetkovic, Z., & Novakovic, B. 2006, Serbian AJ, 173, 73

de Wit, W. J., Testi, L., Pallia, F., & Zinnecker, H. 2005, A&A, 437, 247

Docobo, J. A. 1991, IAU Comm. 26 Inf. Circ., 115

Docobo, J. A. 1996, IAU Comm. 26 Inf. Circ., 129

Docobo, J. A., & Andrade, M. 2005, IAU Comm. 26 Inf. Circ., 156

Docobo, J. A., & Costa, J. M. 1986, IAU Comm. 26 Inf. Circ., 99

Docobo, J. A., & Costa, J. M. 1990, PASP, 102, 1400

Docobo, J. A., & Ling, J. F. 1997, IAU Comm. 26 Inf. Circ., 131

Docobo, J. A., & Ling, J. F. 1998, IAU Comm. 26 Inf. Circ., 135
Niemela, V. S., & Gamen, R. C. 2005, MNRAS, 356, 974
Niemela, V. S., Shara, M., Wallace, D., Zurek, D., & Moffat, A. F. J. 1998, AJ, 115, 2047
North, J. R., Tuthill, P. G., Tango, W. J., & Davis, J. 2007, MNRAS, 377, 415
Nys, O. 1982, IAU Comm. 26 Inf. Circ., 86
Olevic, D. 2002a, IAU Comm. 26 Inf. Circ., 148
Olevic, D. 2002b, IAU Comm. 26 Inf. Circ., 146
Olevic, D., & Cvetkovic, Z. 2003, IAU Comm. 26 Inf. Circ., 149
Olevic, D., & Cvetkovic, Z. 2004, A&A, 415, 259
Olevic, D., & Cvetkovic, Z. 2005a, Serbian AJ, 170, 65
Olevic, D., & Cvetkovic, Z. 2005b, IAU Comm. 26 Inf. Circ., 155
Olevic, D., & Cvetkovic, Z. 2006, AJ, 131, 1721
Olevic, D., & Jovanovic, P. 1997, Bull. Obs. Astron. Belgrade, 155, 103
Patience, J., Ghez, A. M., Reid, I. N., Weinberger, A. J., & Matthews, K. 1998, AJ, 115, 1972
Penny, L. R., Seyle, D., Gies, D. R., Harvin, J. A., Bagnuolo, W. G., Jr., Thaller, M. L., Fullerton, A. W., & Kaper, L. 2001, ApJ, 548, 889
Petro, M. G., Coudé du Foresto, V., Beckwith, S. V. W., Richichi, A., & McCaughrean, M. J. 1998, ApJ, 500, 825
Popovic, G. M., & Pavlovic, R. 1995, IAU Comm. 26 Inf. Circ., 125
Pourbaix, D. 2000, A&AS, 145, 215
Rabe, W. 1948, Astron. Nachr., 276, 262
Romero, F. M. R. 2006a, IAU Comm. 26 Inf. Circ., 158
Romero, F. M. R. 2006b, IAU Comm. 26 Inf. Circ., 160
Romero, F. M. R. 2006c, IAU Comm. 26 Inf. Circ., 159
Romero, F. M. R. 2007, IAU Comm. 26 Inf. Circ., 161
Rossiter, R. A. 1955, Publ. Univ. Michigan Obs., 11, 1
Scardia, M. 1991, IAU Comm. 26 Inf. Circ., 114
Scardia, M., Argyle, R. W., Prieur, J.-L., Pansecchi, L., Basso, S., Law, N. M., & Mackay, C. D. 2007a, Astron. Nachr., 328, 146
Scardia, M., Prieur, J.-L., Aristidi, E., & Koechlin, L. 2000, Astron. Nachr., 321, 255
Scardia, M., Prieur, J.-L., Koechlin, L., & Aristidi, E. 2001, IAU Comm. 26 Inf. Circ., 145
Scardia, M., Prieur, J.-L., Pansecchi, L., & Argyle, R. W. 2007b, IAU Comm. 26 Inf. Circ., 163
Schertl, D., Balega, Y. Y., Preibisch, Th., & Weigelt, G. 2003, A&A, 402, 267
Seymour, D. S., & Hartkopf, W. I. 1999, IAU Comm. 26 Inf. Circ., 139
Seymour, D. S., & Mason, B. D. 1999, IAU Comm. 26 Inf. Circ., 139
Seymour, D. S., & Mason, B. D. 2000a, IAU Comm. 26 Inf. Circ., 140
Seymour, D. S., & Mason, B. D. 2000b, IAU Comm. 26 Inf. Circ., 141
Seymour, D. S., Mason, B. D., Hartkopf, W. I., & Wycoff, G. L. 2002, AJ, 123, 1023
Shatsky, N., & Tokovinin, A. 2002, A&A, 382, 92
Simon, M., Close, L. M., & Beck, T. L. 1999, AJ, 117, 1375
Söderhjelm, S. 1999, A&A, 341, 121
Starikova, G. A. 1978, Astron. Tsirk., 1002, 3
Starikova, G. A. 1980, SvAL, 6, 130
Starikova, G. A. 1981, SvAL, 7, 130
Tamazian, V. S., & Docolo, I. A. 2006, AJ, 131, 2681
Tokovinin, A. A. 1986, SvAL, 12, 201
Tokovinin, A. A. 1997, A&AS, 124, 75 (see current version at http://www.ctio.noao.edu/~atokovin/stars/index.php)
Tokovinin, A. A. 1999, SvAL, 25, 669
Tokovinin, A. A., Kiyeva, O., Sterzik, M., Orlov, V., Rubinov, A., & Zhuchkov, R. 2005, A&A, 441, 695
Turner, N. H., ten Brummelaar, T. A., & Mason, B. D. 2008a, BAAS, 40, 1406
Turner, N. H., ten Brummelaar, T. A., Roberts, L. C., Jr., Mason, B. D., Hartkopf, W. I., & Gies, D. R. 2008b, AJ, 136, 554
Vanbeveren, D., De Loore, C., & Van Rensbergen, W. 1998, A&ARv, 9, 63
van den Bos, W. H. 1956, Union Obs. Circ., 6, 266
Walborn, N. R., et al. 2002, AJ, 123, 2754
Weigelt, G., Balega, Y., Preibisch, T., Schertl, D., Schoeller, M., & Zinnecker, H. 1999, A&A, 347, L15
Wilson, R. H. 1952, AJ, 57, 248
Zaera, J. A. 1985, IAU Comm. 26 Inf. Circ., 96
Zinnecker, H., & Yorke, H. W. 2007, ARA&A, 45, 481
Zirm, H. 2002, IAU Comm. 26 Inf. Circ., 147
Zirm, H. 2007, IAU Comm. 26 Inf. Circ., 161
Zulevic, D. J. 1991, IAU Comm. 26 Inf. Circ., 114
Zulevic, D. J. 1997, Bull. Obs. Astron. Belgrade, 155, 109