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

BRIAN D. MASON1,6, WILLIAM I. HARTKOPF1,6, DEEPAK RAGHAVAN2,6, JOHN P. SUBASAVAGE3,6, LEWIS C. ROBERTS JR.4, NILS H. TURNER5, and THEO A. TEN BRUMMELAAR5

1 United States Naval Observatory, Washington, DC 20392-5420, USA; bdm@usno.navy.mil, wih@usno.navy.mil
2 Department of Physics & Astronomy, Georgia State University, Atlanta, GA 30303-3083, USA; raghavan@chara.gsu.edu
3 Cerro Tololo Inter-American Observatory, La Serena, Chile; jsbasavage@ctio.noao.edu
4 Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA; lewis.c.roberts@jpl.nasa.gov
5 Center for High Angular Resolution Astronomy, Georgia State University, Mt. Wilson, CA 91023 USA; nils@chara-array.org, theo@chara-array.org

Received 2011 June 27; accepted 2011 September 19; published 2011 October 17

ABSTRACT

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

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

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

1. INTRODUCTION

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

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

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

2. SPECKLE OBSERVATIONS

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

Speckle interferometry is a single filled-aperture interferometric technique where the “speckles” of a pair of nearby stars, induced by atmospheric turbulence, constructively interfere. Reduced by simple autocorrelation methods, in the resulting image
the binary or double star geometry is the predominant structure when compared with the other uncorrelated pairings. It is capable of resolving pairs to the resolution limit of the telescope in question up to the size of the observation field (typically, \( \sim 1'5 \)), as long as the pairs have magnitude differences of less than about three.

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

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

3. RESULTS

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

Of the 118 exoplanet hosts we observed only one, HIP 6702 (= HD 8673), appeared double in directed vector autocorrelations on both times it was observed. The classification of HIP 6702 as an exoplanet is based upon Hartmann et al. (2010) who, using iodine-cell radial velocity measurements, detected a companion with an \( M \sin i \) of 14.2 \( M_\oplus \) with a period of 1634 \pm 17 days and an eccentricity of 0.723 \pm 0.016. The relative astrometric measures of this resolved pair are provided in Table 1. Given the small number of measures presented in Table 2, the pair, while a visual double star, is not necessarily a binary system. Verification of physicality for the new companion to HIP 6702 can be accomplished in several ways, among them color–magnitude, proper motion, and/or kinematic analysis. The speckle interferometry observable of relative position establishing kinematic–physical (i.e., Keplerian) motion requires at least three measures. So, while close proximity can be a powerful argument for physicality, it is by no means definitive (cf. \( i \) Ori; Section 5.1 of Mason et al. 2009). Nevertheless, even a companion which is only nearby in the angular sense should be considered in any detailed analysis of the star, as it will contribute to the photometric signature of the examined target. Such is the case for HIP 6702, which was recently reported as a sub-stellar companion (Hartmann et al. 2010).

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

### Table 1

| Coordinates       | WDS or Discoverer Designation | HIP | BY 2000.0+ | \( \theta \) (deg) | \( \rho \) (') | \( \Delta m \) (mag) | Sep (AU) |
|-------------------|-------------------------------|-----|------------|---------------------|--------------|---------------------|--------|
| \( 012608.78 + 343446.9 \) | WSI 96 | 6702 | 1.0193 | 257.3 | 0.087 | 3.3 |
| \( 01262 + 3435 \) | \( 7.6049 \) | \( 78.3 \) | \( 0.109 \) | \( 2.3 \) | \( 4.2 \) |

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

Among the possible interpretations of the new speckle companion two stand out: first, the companion is a non-physically associated line-of-sight companion and second, it is the companion detected in Hartmann et al. (2010).
### Table 2
Stars with No Companion Detected (Continued)

| HIP  | HD   | Common Name | BY 2000.0+ | Telescope |
|------|------|-------------|------------|-----------|
| 57291| 102117|             |            |            |
| 57370| 102195|             |            |            |
| 57443| 102365|             |            |            |
| 57443| 102365|             |            |            |
| 57931| 103197|             |            |            |
| 58451| 104067|             |            |            |
| 59610| 106252|             |            |            |
| 62495| 114386|             |            |            |
| 64426| 114762|             |            |            |
| 64457| 114783|             |            |            |
| 64459| 114729|             |            |            |
| 64459| 114729|             |            |            |
| 64924| 115617| 61 Vir      | 6.1890 C   |            |
| 64924| 115617| 61 Vir      | 8.4500 K   |            |
| 65721| 117176| 70 Vir      | 10.0688 C  |            |
| 65721| 117176| 70 Vir      | 6.1916 C   |            |
| 67275| 120136|            | 1.0314     |            |
| 67275| 120136|            | 6.1916 C   |            |
| 71305| 128311|             | 1.5664 C   |            |
| 71305| 128311|             | 6.1916 C   |            |
| 72339| 130322|             | 1.0829 C   |            |
| 74500| 134987|             | 1.0830 C   |            |
| 74500| 134987|             | 1.5611 C   |            |
| 77740| 141937|             | 1.5666 C   |            |
| 79242| 142022A|            | 1.5667 C   |            |
| 79248| 145675| 14 Her      | 1.4986 K   |            |
| 80250| 147018|             | 1.5667 C   |            |
| 80337| 147513|             | 6.1919 C   |            |
| 83589| 154345|             | 1.4960 K   |            |
| 83949| 155538|             | 1.4961 K   |            |
| 86796| 160691|            | 1.5667 C   |            |
| 87330| 162020|             | 1.5642 C   |            |
| 88348| 164922|             | 8.4506 K   |            |
| 90004| 168746|             | 1.5614 C   |            |
| 90485| 169830|             | 1.5614 C   |            |
| 91085| 171238|             | 1.5614 C   |            |
| 94075| 178911B|            | 1.4990 K   |            |
| 94645| 179949|             | 1.5614 C   |            |
| 96901| 186427| 16 Cyg      | 1.4991 K   |            |
| 97336| 187123|             | 1.4990 K   |            |
| 97546| 187085|             | 1.5670 C   |            |
| 98505| 189733|             | 8.4614 K   |            |
| 98767| 190360|             | 8.4563 K   |            |
| 99711| 192263|             | 5.8680 K   |            |
| 99825| 192310| 70 Vir      | 1.5616 C   |            |
| 101806| 196050|             | 1.5615 C   |            |
| 101966| 196885|             | 8.4481 K   |            |
| 104903| 202206|             | 1.5618 C   |            |
| 106006| 204313|             | 1.5618 C   |            |
| 106353| 204941|             | 1.5618 C   |            |
| 108375| 208487|             | 1.5672 C   |            |
| 108859| 209458|             | 8.4615 K   |            |
| 109378| 210277|             | 1.5645 C   |            |
| 111143| 213240|             | 1.5618 C   |            |
| 112441| 215497|             | 1.5646 C   |            |
| 113137| 216437|             | 1.5647 C   |            |
| 113238| 216770|             | 1.5646 C   |            |
| 113557| 217014| 51 Peg      | 7.5883 K   |            |
| 113557| 217014| 51 Peg      | 8.4617 K   |            |
| 116727| 222404| 30 Ari      | 1.0218 K   |            |
| 116727| 222404| 30 Ari      | 1.4993 K   |            |
| 116906| 222582|             | 1.5674 C   |            |

| HIP  | HD   | Common Name | BY 2000.0+ | Telescope |
|------|------|-------------|------------|-----------|
| 32916| 49674|             |            |            |
| 32970| 50499|             |            |            |
| 33212| 50554|             |            |            |
| 33719| 52265|             |            |            |
| 36795| 60307|             |            |            |
| 37826| 62509|             |            |            |
| 38041| 63765|             |            |            |
| 38558| 65216|             |            |            |
| 40693| 69830|             |            |            |
| 40952| 70642|             |            |            |
| 43587| 75732| 55 Cnc      |            |            |
| 46076| 81040|             |            |            |
| 47007| 82943|             |            |            |
| 47202| 83443|             |            |            |
| 48235| 85390|             |            |            |
| 48739| 86226|             |            |            |
| 49699| 87883|             |            |            |
| 50473| 89307|             |            |            |
| 50921| 90156|             |            |            |
| 52521| 93083|             |            |            |
| 53721| 95128|             |            |            |
| 54906| 97658|             |            |            |
| 57172| 101930|            |            |            |
3.1.1. Physical Companion?

Hipparcos has produced many types of double star solutions. The ones which can be most easily compared to other detection techniques and the most common are those where the relative parameters ($\rho, \theta$) are presented. The speckle interferometry measures presented in Table 1 are both near the Hipparcos “C” code double star solution cutoff (0.082 for HDS 446 = HIP 27151). The other Hipparcos double star solutions may not be applicable here. Some depend upon a priori orbital information (O code), system dynamics in the plane of the sky (G code), variability (V code), or unknown parameters (X and/or S code). In any event, the lack of Hipparcos detection is a condition which is neither necessary nor sufficient to establish that the Hartmann et al. (2010) companion is not stellar.

However, if the two Table 1 measures represent relative measures of the Hartmann et al. (2010) pair, the inclination must be extremely low. Assuming a near zero inclination the mean separation of $0.098$ would approximate the angular semi-major axis ($a'' = 0.098 \pm 0.011$). Given this, the Hipparcos parallax of $26.14 \pm 0.79$ mas and the Hartmann et al. period of $1634 \pm 17$ days, a mass sum of $2.63 \pm 0.92 M_\odot$ is obtained, which is not unreasonable for two similar F dwarf stars, although the error is quite large, primarily due to the uncertainty in $a''$. The length of time between the two speckle observations represents 1.47 times the Hartmann et al. period. The two measures of angular position represent ($0.497$ or $0.503$) + $n$ revolutions of the system (depending on the direction of rotation), which is very similar to the Hartmann et al. period when $n = 1$.

Given the estimated dynamic range ($\Delta m_V = 2.3 \pm 0.5$) and assuming the fainter limit and spectral type of the primary this would make the secondary close to a K2V. Using the canonical mass of a K2V in $M \sin i = 14.2 M_J$ gives an inclination of $1^\circ.02$. Using this inclination with $a \sin i$ from Hartmann et al. (2010) gives a semi-major axis of $0.168$ which is consistent with the Table 1 results.

3.1.2. Optical Companion?

Since the interferometric companion to HIP 6702 has been observed so few times, establishing the companion as optical or physical is not possible. The proper motion of the primary is $0.25$ yr$^{-1}$ ($\alpha = 0'.236$ yr$^{-1}$, $\delta = -0'.085$ yr$^{-1}$). From the relative positions in Table 1, the proper motion of the companion would be an even higher at $0.276$ yr$^{-1}$. If linear motion is assumed and reasonable errors are applied it is possible to determine where the companion would be at some date in the future. In Figure 1, this determination is performed assuming errors slightly larger than nominal for the two speckle interferometry measures: $\Delta \theta = 1'0$, $\Delta \rho/\rho = 1.0\%$. The predicted position for 2012 through 2015 are plotted as error boxes. Again, assuming linear motion from the two speckle points, a separation of $0'.37$ and a position angle of $255^\circ$ is determined for 1991.25, at the Hipparcos epoch.

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

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

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

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

4. FUTURE OBSERVING

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

The USNO speckle interferometry program has been supported by NASA and the SIM preparatory science program through NRA 98-OSS-007, SIM Key Project MASSIF as well as No. NNH06AF701 issued through the Terrestrial Planet Finder Foundation Science program. Thanks are also expressed to the U.S. Naval Observatory for their continued support of the Double Star Program. A portion of the research in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA). This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. Grateful acknowledgment is given to USNO interns Dean Kang, Laura Flagg, and Ankit Patel for their processing of the speckle pixel data. The telescope operators and observing support personnel of KPNO and CTIO continue to provide exceptional support for visiting astronomers. Thanks to Alberto Alvarez, Skip Andree, Bill Binkert, Gale Brehmer, Bill Gillespie, Angel Guerra, Jim Hutchinson, Hillary Mathis, Oscar Saa, Patricio Ugarte, and the rest of the KPNO and CTIO staff. We also thank Richard Green of KPNO, who was able to provide us with two extra nights on the 4 m Mayall telescope during our

2001 January run. While we were hampered by poor weather, this additional allocation of time certainly helped us achieve a greatly enhanced completion fraction. A special thanks is also given to Hal Halbedel, who operated the telescope on all or part of each of these new KPNO runs and was instrumental in the slit-mask work done at KPNO.

**APPENDIX**

**ADDITIONAL MEASURES OF KNOWN PAIRS**

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

---

\(^7\) http://nsted.ipac.caltech.edu/cgi-bin/bgServices/nph-bgExec, extracted 2011 April 12.

---

| WDS or a.d. (2000) | Discovery Designation | HIP | BY | \(\theta\) | \(\rho\) | Note |
|---------------------|----------------------|-----|----|------|----|------|
| 00024 + 1047 A      | 1249 AB              | 190 | 7.5994 | 74.8 | 0.135 |      |
| 00026 – 0829 A      | 428                  | 210 | 7.6019 | 344.5 | 0.174 |      |
| 00055 – 1835 RST    | 3340                 |     | 1.5701 | 287.4 | 0.303 |      |
| 00095 + 1907 COU    | 247                  | 768 | 7.5992 | 259.1 | 0.294 |      |
| 00117 + 6145 TDS    | 1338                 |     | 7.6074 | 111.2 | 0.527 | 1    |
| 00167 + 3629 STT    | 4                    | 1336| 7.6021 | 99.7  | 0.232 |      |
| 00174 + 0853 A      | 1803 AB              | 1392| 7.6019 | 307.2 | 0.145 |      |
| 00182 + 7257 A      | 803                  | 1461| 7.6021 | 307.9 | 0.262 |      |
| 00233 + 5132 TDS    | 1431                 |     | 7.6074 | 202.5 | 0.227 | 1    |
| 00271 – 0753 A      | 431                  | 2143| 1.5021 | 384.5 | 0.139 |      |
|                     |                      |     | 1.5647 | 189.0 | 0.139 |      |
|                     |                      |     | 7.6019 | 13.3  | 0.201 |      |

**Notes.**

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

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)
positions for 485 known systems. Column 1 is the WDS identification (arcminute coordinate), Column 2 lists the discovery designation, and Column 3 provides the Hipparcos number. Column 4 gives the epoch of observation, and Columns 5 and 6 provide the relative astrometry. Column 7 contains the notes for these systems. Also found in the table are 10 pairs resolved for the first time and 60 pairs which are here confirmed; estimated magnitude differences for the new pairs (when available) are listed in the notes column.

REFERENCES

Bagnuolo, W. G., Jr., Mason, B. D., Barry, D. J., Hartkopf, W. I., & McAlister, H. A. 1992, AJ, 103, 1399
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Harrington, R. S. 1981, in Life in the Universe, ed. J. Billingham (Cambridge: MIT Press), 119
Hartkopf, W. I., Mason, B. D., McAlister, H. A., et al. 2000, AJ, 119, 3084
Hartmann, M., Guenther, E. W., & Hatzes, A. P. 2010, ApJ, 717, 348
Jao, W.-C., Mason, B. D., Hartkopf, W. I., Henry, T. J., & Ramos, S. N. 2009, AJ, 137, 3800
Mason, B. D., Hartkopf, W. I., Gies, D. R., Henry, T. J., & Helsel, J. W. 2009, AJ, 137, 3358
Mason, B. D., Hartkopf, W. I., & Wycoff, G. L. 2011, AJ, 142, 46
Mason, B. D., Wycoff, G. L., Hartkopf, W. I., Douglass, G. G., & Worley, C. E. 2001, AJ, 122, 3466 (The Washington Double Star Catalog, published in Second USNO Double Star CD 2006.5 and available online at http://ad.usno.navy.mil/wds/wds.html.)
Perryman, M. A. C., & ESA 1997, The Hipparcos and Tycho Catalogues (ESA SP-1200: Noordwijk: ESA)
Raghavan, D., Henry, T. J., Mason, B. D., et al. 2006, ApJ, 646, 523
Raghavan, D., McAlister, H. A., Henry, T. J., et al. 2010, ApJS, 190, 1
Roberts, L. C., Jr., Turner, N. H., ten Brummelaar, T. A., Mason, B. D., & Hartkopf, W. I. 2011, AJ, 142, 175
Tokovinin, A., Mason, B. D., & Hartkopf, W. I. 2010, AJ, 139, 743