

Lucky Imaging Astrometry of 59 Andromedae

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Abstract: Students from Arroyo Grande High School, as members of a Cuesta College research seminar, observed the double star 59 Andromedae (02109+3902 STF 222) using the lucky imaging technique. The measured separation was 16.16" and the position angle was 36.33°. The pair has maintained approximately the same separation and position angle since observations began in 1873. Consideration of historic observations, proper motion vectors, and parallaxes were insufficient to conclude whether the double was a chance optical double, a gravitationally bound binary, or a common proper motion pair.

Introduction

This paper reports on one of four double star research projects that were part of the Fall 2012 Cuesta College Astronomy Research Seminar held at Arroyo Grande High School. Observations were conducted at the Orion Observatory near Santa Margarita Lake, California, on the nights of November 11 and 12, 2012 (B2012.865 and B2012.868) with a Sidereal Technology controlled 10-inch Meade LX200 telescope equipped with an Andor Luca-S electron-multiplying CCD camera.

The primary objective of this project was to add a current observation of the position angle and separation of 59 Andromedae to the growing set of observations that began over two centuries ago. The secondary objectives were to provide students with an opportunity to collect data utilizing lucky imaging (an advanced technique), reduce and analyze their data, and determine if



Figure 1: From left to right: Bobby Johnson, Everett Heath, Sophia Bylsma, Cameron Arnet, Kaela Yancosek, and Jason Olsen.

the double star is likely optical or binary in nature.

The double star 59 Andromeda (WDS 02109+3902 STF 222) was chosen as a wide pair ap-

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appropriate for observation without supplemental magnification. Three sets of observations were made as detailed below: (1) drifts to determine the camera's angle with respect to north, (2) observations of two standard double stars to determine both the camera's orientation and pixel plate scale, and (3) observations of 59 Andromedae itself.

Lucky Imaging

The atmosphere is composed of many small air cells of slightly different temperature and density (Fried 1966, Tatarski 1961). Each cell is typically about eight inches across. The cells deflect the path of starlight as they move across the telescope's field-of-view, causing the rapid movement of stars (jitter) which blurs the star's image during normal exposures. This degrading effect of "seeing" can be reduced by locating telescopes on high altitude mountaintops.

For a very small area of the sky, about 10 arc seconds in diameter, known as an "isoplanatic patch," the effects of poor seeing can be greatly reduced through lucky imaging or speckle interferometry (Law 2006). Within the isoplanatic patch, the jitter motion of stars is correlated—*i.e.* stars move together. By taking very short exposures (10 to 30 milli-seconds) it is possible to essentially "freeze" the images and thus remove the tip-tilt portion of the atmospheric blurring (seeing) effects (Anton 2012).

Even then, most images are still blurry. Fortunately, a small percentage can be quite clear. However, due to the short exposures, these few clear exposures are also faint. Lucky imaging simply takes many short exposures, saves the best ones, and discards the rest of them. Since the small percentage of clear exposures still "bounce" around from one exposure to the next due to atmospheric jitter, they have to be individually aligned. Once aligned, the images can then be "stacked," essentially adding all the clear images together to form a final, brighter and higher signal/noise ratio, single image. The selection of the clearest images (from hundreds or even thousands) and aligning and stacking these images has been automated.

Equipment and Software

At the Orion Observatory, a 10-inch, f/10 Schmidt-Cassegrain telescope, made by Meade and equipped with a Sidereal Technology control system, was used to make the observations. An 80 mm guide scope, equipped with a Santa Barbara Instruments Group

(SBIG) ST-402 CCD camera, provided field identification and initial centering.

A high-speed Andor Luca-S electron multiplying CCD camera was used (unfiltered and without any Barlow lens) for lucky imaging astrometry. This camera's high speed is achieved, in part, through a software-selectable Region of Interest (RoI), allowing just a small portion of the overall pixel array to be read out.

Normally, reading out a CCD camera at high speed is much noisier than at slow speeds due to the inherent nature of analog-to-digital (A/D) converters. However, by adding a special row of pixels to the chip just before the A/D converter, with each pixel in this row being at a slightly higher voltage level than its predecessor, the electron charges corresponding to the observed light levels can be multiplied by a factor of up to 1000 as they are clocked through this electron multiplying row. Although this amplification in itself introduces some noise, for high speeds and low light levels this added noise is small compared to the high speed read noise of the A/D converter and, as a result, the overall noise is greatly reduced from what it would have been without electron multiplication (EM).

Finally, it might be noted that although EM can greatly reduce overall noise at high speeds, at the slow readout speeds of many CCD applications the read noise is comparatively low and EM can actually increase overall noise. The Andor Luca-S camera has two different selectable outputs—one with and one without EM, allowing the camera to be used in a mode

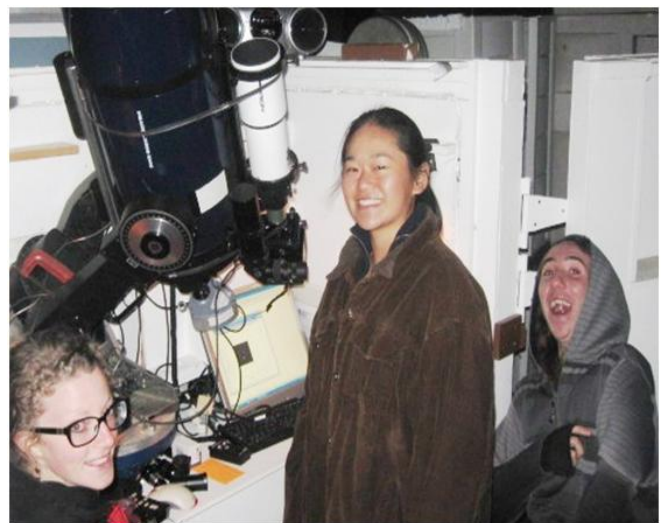


Figure 2: Sophia Bylsma, Anna Zhang, and Everett Heath at the Orion Observatory. The Andor Luca-S high-speed emCCD camera can be seen just below the telescope.

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suitable to the situation at hand.

The telescope was controlled with hardware and software supplied by Sidereal Technology. Software Bisque's *The Sky 6* was used as the "planetarium" program, while the SBIG ST-402 camera was controlled with Software Bisque's *CCD Soft*. The Andor Camera was controlled with Andor's *SOLIS*. The data was initially gathered as data cubes in the Andor camera's native .sif format. A *SOLIS* batch conversion process was used to transform and unpack the cubes to produce individual .fit images. Finally, the data was analyzed with *REDUC*, a sophisticated freeware double star analysis program developed by Florent Losse, a very active double star observer in France.

Calibration

Calibration observations were made on the second night. The camera had not been moved in any way between the two nights. "Drifts" were obtained by moving a bright star to one edge of the camera's field and then temporarily turning off the telescope's drive, causing the star to drift across the field-of-view as the Earth turned while multiple images were taken. A feature of *REDUC* provides a least squares fit of a straight line through the star's centroids on the multiple images, thus establishing an east-west line from which the orientation (angle) of the camera with respect to North can be deduced. Five drifts were obtained so we could estimate the precision (standard error of the five means) with which the camera's angle with respect to celestial north was being determined.

Observations were also made of two calibration binary stars, STF 742 and STT 547. These binaries have well-established orbits and, at any point in time, their position angle and separation can be determined via simple interpolations from a catalog of ephemerides provided by the U.S. Naval Observatory. We performed these interpolations. We calculated these for STF 742 as a position angle of 275.2 degrees and a separation of 4.1 arc seconds. These values for STT 547 were, respectively, 187.2 degrees and 5.9 arc seconds. Two different ephemerides were reported in the *Sixth Orbit Catalog* - we used the first one. Each calibration binary observation consisted of 2000 exposures which we divided into four sets of 500 exposures. Each set was then analyzed with *REDUC* for the "best" exposures, using the "brightest pixel" technique. The light on the poor, blurry images is more spread out, while sharp images have concentrated light with higher

pixel values. The exposures were then rank-ordered, and the top 10% of the images were saved while the lower 90% were discarded. The remaining images (50 of 500) were then aligned and stacked. With the position angle and separation of the calibration pair known, the camera position angle and plate scale (arc seconds per pixel) for each set were provided by *REDUC*, and we calculated the means, standard deviations, and standard errors of the mean across the four sets.

Our calibration results are shown in Table 1. The calibration pair STT 547 provided the most precise results, with standard deviations of less than one half of those of the other calibration pair, STF 742, and (for the camera angle) less than one third that of the drifts. While we could have used some precision-weighted means to combine all three of our calibration results, we chose instead to exclusively utilize the most precise results, those of STT 547.

Although we are reasonably confident in the precision of our three calibration results, as given in Table 1, they are in disagreement in their means beyond the one sigma level, suggesting a systematic difference. This could have been a result of the calibration pairs not being positioned sufficiently close in the sky to the program pair, and hence inaccuracies in the polar alignment of the telescope could have affected accuracy, as the field will rotate with changes in the telescope's position with poor axis alignment.

There were insufficient calibration observations to estimate their accuracy; we expect that their accuracy could be less than could have been achieved for two reasons. First, observations of the program star (59 Andromedae) were made on the first night, while calibration observations of the two calibration binaries were made on the second night. Although we were careful not to move the camera in any way during the two nights (and seeing and other observing conditions were similar), if our program observations had been brack-

Table 1: Calibration results: The camera angles and scale factors and standard deviations.

	Angle (degrees)	One Sigma Std. Dev.	Scale Factor (Arcsec/ Pixel)	One Sigma Std. Dev.
Drifts	-7.63	0.25	N/A	N/A
STF 742	-8.33	0.19	0.229	0.0008
STT 547	-7.93	0.07	0.222	0.0003

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Table 2. Separation, position angle, and difference in magnitude measurements for 59 Andromedae with the averages, standard deviations, and standard errors of the mean.

Besselian Epoch	Frames	Sep. (arc sec)	PA ($^{\circ}$)	dMag
B2012.865	000-499	16.156	36.18	1.08
B2012.865	500-999	16.136	36.44	1.10
B2012.865	1000-1499	16.167	36.38	1.07
B2012.865	1500-1599	16.209	36.27	1.06
B2012.865	2000-2499	16.149	36.40	1.07
	Average	16.160	36.33	1.08
	St. Dev.	0.03	0.11	0.02
	St. Err. Mean	0.01	0.05	0.01

eted with calibration observations we could have developed confidence in the constancy of the camera's orientation and pixel plate scale.

Program Observations

Altogether 2500 frames (images) were recorded for 59 Andromedae. Similar to the calibration doubles, we split the data into sets of 500 frames each, applied *REDUC*'s "best of max" brightest pixel sorting to each of the five sets, saved the best 10% (50 frames from each set), and aligned and stacked these images. Assuming the camera angle and plate scale provided from our observations of the calibration pair STT 547, we obtained the program results shown in Table 2.

It is instructive to compare, for the same total integration time, what the image looks like with and without lucky imaging. Figure 3, left, shows the image that results from stacking all 500 frames of the first set without any selection or alignment—the "raw" image. The image on the right is of the best 50 of the 500 frames shown after both alignment and stacking—the lucky image. The lucky image is much more sharply defined (higher resolution) and, as a result, provides astrometry of significantly higher precision.

These two images clearly demonstrate how well lucky imaging can overcome atmospheric distortions (not to mention poor tracking). Because the centroids of the individual stars can be more precisely determined with lucky imaging, it follows that the position angle and separation will also be more precise. Furthermore, if the separation of the two stars had been so close that the raw image stars were merging together into a single image, the stars in the lucky image could still have been resolvable and usable. Thus lucky imaging not only allows higher precision, but also closer doubles to be measured.

Comparison with Previous Observations

William Herschel, in 1783, was the first astronomer to report the separation and position angle of the 59 Andromedae pair (Smyth 1844). John Herschel and James South observed this double in 1822 (South and Herschel 1824). Friedrich von Struve, for whom the STF designation was given, observed 59 Andromedae twice, in 1822 and 1831 (Struve 1837). Recently, David Arnold visually observed the pair in 2005 (Arnold

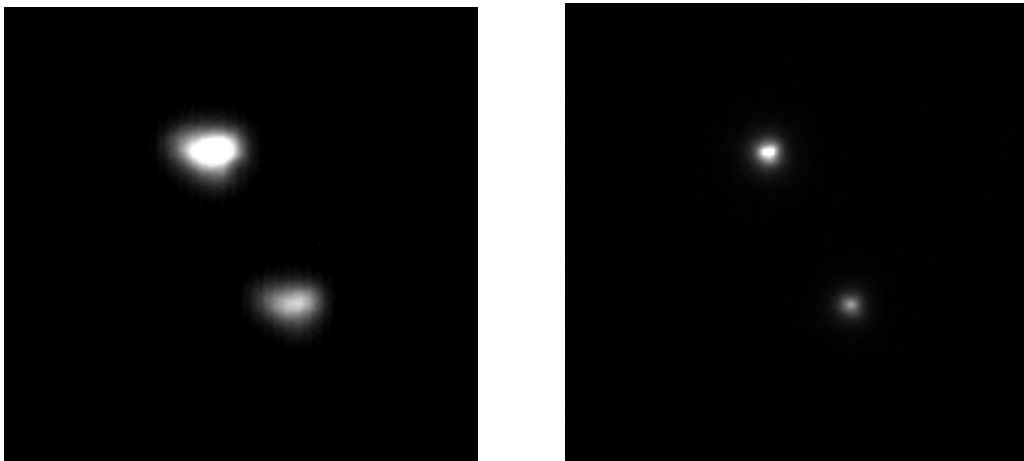


Figure 3: Left is the first 500 images just stacked. Right is the best 10% of the first 500 images (i.e. 50 images) stacked and aligned.

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2006). Mason, et al. used speckle interferometry to measure this double in 2006, 2007, 2008, and 2011 (Mason, et al. 2007, 2008, and 2010, and Mason and Hartkopf 2013). A total of 83 measurements of separation and 85 of position angle have been made since 1783.

This double does not have an ephemeris in either the *Sixth Orbit Catalog* or the *Catalog of Rectilinear Elements*. To consider, roughly, the accuracy of our measured separation and position angle, an average of observations over the last 25 years was used as a comparison. The past observations were supplied by Brian Mason at the US Naval Observatory. The average

separation of the past 25 years is 16.68" while our observed separation in the present study was 16.16", a 0.52" difference. The average position angle of the past 25 years is 35.60° while our observed position angle in the present study was 36.33°, a 0.73° difference.

Another way of considering comparisons with previous observations is viewing visual plots. Ed Wiley kindly plotted our data using a spreadsheet developed by Francisco Rica Romero. The observations were corrected for precession and proper motion prior to plotting and converted to Cartesian coordinates. X and Y plots versus epoch are shown in Figures 4 and 5, while Figure 6 is a cluster plot of the X/Y positions without

STF222 X versus Epoch

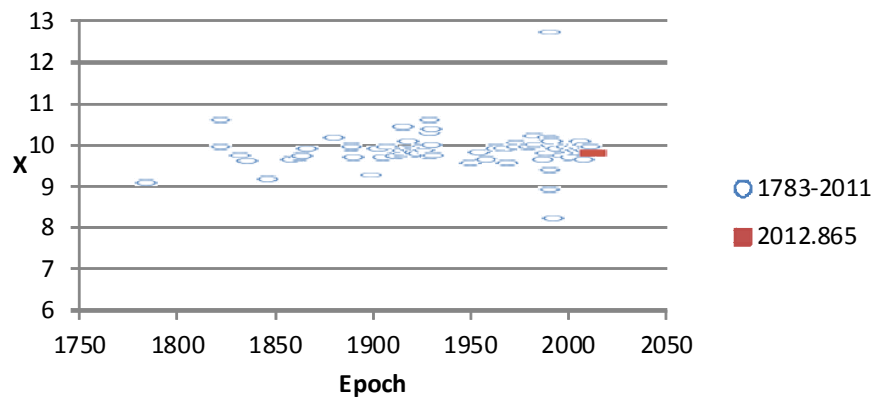


Figure 4: X values versus epoch. Open circles are previous observations, while the filled square is our observation

STF 222 Y versus Epoch

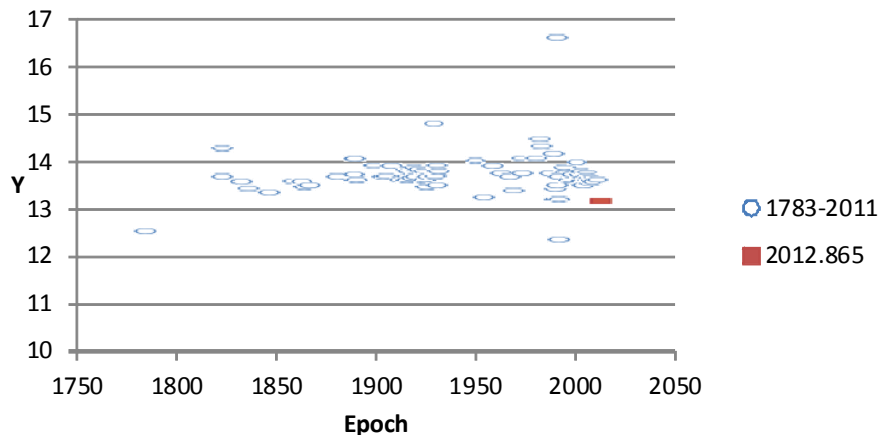


Figure 5: Y values versus epoch.

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STF222 Cluster Plot

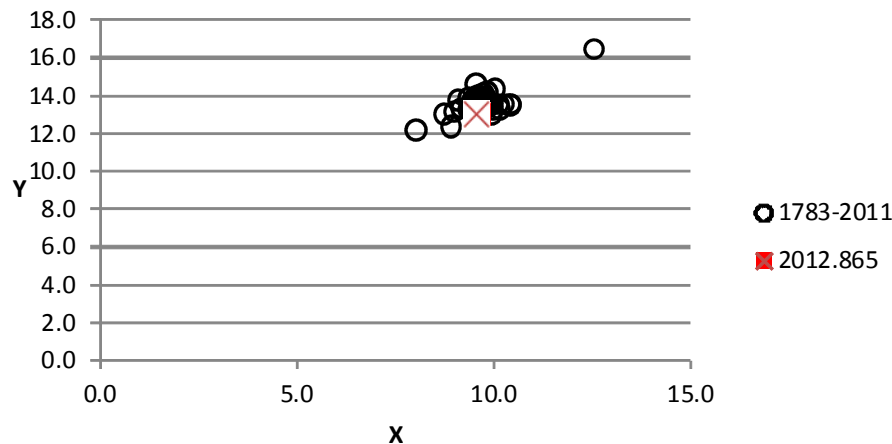


Figure 6: Cluster plot of X and Y positions plotted as a cluster without epoch information. The result is a fairly tight cluster. Our observation is not an outlier.

respect to epoch.

Is 59 Andromedae an Optical Double or a Binary?

All nine measurements from the first 50 years of observation, beginning in 1822, were averaged to determine how the pair has changed over time. The average separation of the first 50 years, as show in Table 3 is 16.53", a 0.15" difference from the average over the last 25 years. The average position angle of the first 50 years is 34.89°, a 0.71° difference from the last 25 years. Both differences are within a single standard deviation and are therefore insignificant.

The spectral type of 59 Andromedae’s primary component (SAO 55330) is B9V and its magnitude is 6.05 (SIMBAD 2012). The spectral type of the secondary component (SAO 55331) is A1V and its magnitude is 6.71 (SIMBAD 2012). The B9 and A1 stars probably have a similar brightness because they are

each just one tenth of a “class” away from A0. Since their spectral types are so similar and both are on the main sequence, the stars could be roughly the same distance from Earth.

On the other hand, SAO 55330 has a parallax of 0.01241" ± 0.00283" which corresponds to a distance of 263 light years (SIMBAD 2012). SAO 55331 has a parallax of 0.00192" ± 0.01175" which yields a distance of 1699 light years (SIMBAD 2012). However, the error for the secondary star's distance is sizable, ranging from 236 light years to infinity (SIMBAD 2012). Thus, based on parallaxes, it is possible, though unlikely, that the two stars are at the same distance from Earth. If both stars were 263 light years from earth (and the average separation of the past 25 years of 16.68" is correct), they would be ~1.22 light years (77,154AU) apart—perhaps too far apart to be gravitationally bound, but close enough to be a common proper motion pair.

Table 3: Average separation and position angle for observations in the first 50 years and last 25 years with standard deviations and standard errors of the mean.

	First 50 Years Sep (")	Last 25 Years Sep (")	Diff (")	First 50 Years PA (°)	Last 25 Years PA (°)	Diff. PA (°)
Average	16.53	16.68	0.15	34.89	35.60	0.71
St. Dev.	0.37	0.92		0.93	0.90	
St. Err. Mean	0.07	0.17		0.17	0.17	

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Finally, double stars are most likely binary if the proper motion vectors of the two stars are similar. The proper motion (in milliarcseconds per year) of SAO 55330 is -7.99 in RA and -19.97 in Dec (SIMBAD 2012). The proper motion of SAO 55331 is -7.60 in RA and -21.52 in Dec (SIMBAD 2012). These values are of similar magnitude and direction, suggesting that 59 Andromedae may be binary or at least a common proper motion pair.

Conclusions and Recommendations

While some of Cuesta College's Astronomy Research Seminar projects continued this fall to make double star measurements with astrometric eyepieces as in the past, this was the first semester we employed the more advanced and precise technique of lucky imaging. We were pleased with our results and recommend that at least some future teams continue to use the Andor Luca-S high speed EMCCD camera for their projects.

In analyzing whether or not 59 Andromedae is merely a chance optical double, a gravitationally bound binary, or a common proper motion pair, we were unable to draw a decisive conclusion due to the conflicting brightness, parallax, and proper motion evidence.

We recommend that future projects improve on our calibration procedures by observing nearby calibration standards both before and after program pair observations. Future student projects might consider reporting on more than one program double in a single paper. They could also observe much closer doubles.

Finally, future projects might attempt to observe very close doubles. Rainer Anton suggested that an interesting comparison could be made between lucky imaging observations of a fairly faint, close double with and without the camera's electron multiplication. Instead of lucky imaging, a student team might attempt speckle interferometry, although this could require significant supplemental magnification to bring out the "speckles." In addition to magnification, use of a filter to limit the bandwidth and chromatic effects might sharpen the speckles.

Acknowledgments

We thank Florent Losse for use of his *REDUC* software, the American Astronomical Society for providing a Small Research Grant to purchase the Andor Luca-S camera, Andor for supplying the camera at a discounted cost, and Jordan Fluitt for aiding us in observations. We thank Ed Wiley and Francisco Rica Romero for the

positional plots. In addition, we made use of the U.S. Naval Observatory's Washington Double Star Catalog and the SIMBAD data base at CDS. We thank our external reviewers: Rainer Anton, Robert Buchheim, Thomas Frey, John Martinez, Tom Smith, Vera Wallen, and Ed Wiley. Finally, we would like to thank the Orion Observatory for the use of their equipment and hospitality.

References

- Anton, Rainer, 2012, Lucky imaging. In *Observing and Measuring Visual Double Stars 2nd Edition*, Robert Argyle, ed., Springer, New York.
- Arnold, Dave, 2006, Divinus Lux Observatory Bulletin: Report #6. *Journal of Double Star Observations.*, **2**, 87.
- Fried, D. L., 1966, Optical resolution through a randomly inhomogeneous medium for very long and very short exposures, *Optical Society of America Journal*, **56**, 1372.
- Johnson, Jolyon, 2008, Double star research as a form of education for community college and high school students. In *Proceedings for the 27th Annual Conference for the Society for Astronomical Sciences*. Brian Warner, Jerry Foote, David Kenyon, and Dale Mais, eds., Society for Astronomical Sciences, Big Bear, CA.
- Law, Nicholas, 2006, Lucky imaging: diffraction-limited astronomy from the ground in the visible. Doctoral dissertation, Cambridge University.
- Mason, Brian D., William I. Hartkopf, Gary L. Wycoff, and G Wieder. 2007. Speckle Interferometry at the US Naval Observatory, XIII. *Astronomical Journal*. **134**:4, 1671.
- Mason, Brian D., William I. Hartkopf, and Gary Wycoff, 2008, Speckle Interferometry at the US Naval Observatory, XIV, *Astronomical Journal*, **136**, 2223.
- Mason, Brian D., William I. Hartkopf, and Gary Wycoff, 2010, Speckle Interferometry at the US Naval Observatory, XV, *Astronomical Journal*, **140**, 480.
- Mason, Brian D. and William I. Hartkopf, 2013, *Astronomical Journal*, in press.

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SIMBAD Astronomical Database, Centre de Données
Astronomiques de Strasbourg. December 7, 2012.
simbad.u-strasbg.fr/simbad/.

Smyth, William, 1844, *Cycle of Celestial Objects Vol-
ume 2*.

South, James and John Herschel, 1824, Observations of
the apparent distances and positions of 380 double
and triple stars, made in the years 1821, 1822, and
1823, and compared with those of other astron-
omers; Together with an account of such changes as
appear to have taken place in them since their first
discovery. Also a description of a five-foot equato-
rial instrument employed in the observations, *Phi-
losophical Transactions of the Royal Society*, **114**,
1-412.

Tatarski, V., 1961, *Wave Propagation in a Turbulent
Medium*, McGraw-Hill, New York.

von Struve, Friedrich Wilhelm, 1837, Stellar duplicium
et multiplicium mensurae micrometricae, *Petropoli*.

