Astrometric Measurements of Double Stars HJ 4194 and HJ 4195

Vincent Aguilar[1], Emmanuel Mercado[1], Hugh Le[1], Tianlin Zhao[1], Jae Calanog[1], Grady Boyce[2], and Pat Boyce[2]

1. San Diego Miramar College, San Diego, California USA
2. Boyce Research Initiatives and Education Foundation (BRIEF), San Diego, California, USA

Abstract: We performed astrometric measurements on the double stars WDS 08562-8341 (HJ 4194) and WDS 09135-6455 (HJ 4195) through images acquired by the Las Cumbres Observatory telescope network (LCO), using a 0.4-meter Meade telescope to image our selected double stars. The Our Solar Sibling pipeline (OSS) processed and calibrated the images, which were then analyzed using the software Mira Pro x64. From the images of HJ 4194, we calculated the mean position angle of 81.6° ±0.4°, and the separation of 18.2" ± 0.1". From the images of HJ 4195, we calculated the mean position angle of 69.6° ± 0.7°, and separation of 16.3" ± 0.2". We concluded that the data suggests that HJ 4194 is an optical double, while HJ 4195 remains undetermined.

Introduction

Position angle (θ) and separation (ρ) measurements from observing double stars can be used in combination with historical data to determine whether the double star is a gravitationally associated binary star or an optically aligned double star. If a double star is found to be a binary star, then the total system mass can be estimated using the orbit of the system. Understanding the mass of a star is the most fundamental parameter in understanding stellar astrophysics.

We aim to measure the position angle (θ) and separation (ρ) of the neglected double stars HJ 4194 and HJ 4195. Both parameters are important in determining if a secondary star is orbiting around a primary star. If a cartesian graph is made using the historical θ and ρ, and it shows that the data points of the secondary star are approximating an ellipse or part of an ellipse, then the pair is a binary star. Similarly, these same parameters can be used to determine if the secondary star is moving away from the primary star with linear motion indicating a non-gravitationally bound optical double star.

We used the Washington Double Star catalog (WDS) by Brian Mason (2012) to select the double stars in our study. The following general criteria was used to select candidate double stars:

- Right Ascension (RA) hour between 8-14 and therefore visible in the Spring.
- Declination South of -25° (Telescope is in Sutherland, South Africa)
- Difference in magnitudes (Δ Magnitude) < 1
- Separation > 6 arcseconds; distinguishes primary from secondary.
- Recognizable change in position angle.

Sir John F.W. Herschel discovered HJ 4194 and HJ 4195 in 1836. Herschel was an eminent Victorian scientist that contributed to many areas of science. Herschel discovered these double stars during an extensive telescopic survey of the southern sky from the Cape of Good Hope Observatory (The Editors of Encyclopedia Britannica, 2018). Today, the Cape of Good Hope Observatory is recognized as the headquarters of the South African Astronomical Observatory (SAAO), where our images were taken. Herschel's measurements are recorded in the WDS catalog, along with other historical measurements, and are shown in Tables 1 and 2 (Mason et al, 2012).

Table 1: All historical θ and ρ measurements for HJ 4194 found in the WDS. The table shows a large change in position angle and separation over the past 163 year.

HJ 4194 WDS 08562-8341		
Epoch	**θ (°)**	**ρ (arcseconds)**
1836.62	46.60°	10.00"
1882.35	52.80°	12.11"
1895.22	57.60°	15.20"
1902.24	59.40°	15.99"
1903.02	57.60°	15.81"
1919.24	62.20°	16.22"
1956.16	69.40°	16.04"
1991.70	77.30°	17.57"
1998.13	78.20°	17.73"
1999.99	79.00°	17.60"

Table 2: All historical θ and ρ measurements for HJ 4195 from the WDS. The table shows a small change in position angle, and an insignificant change in separation over the past 175 years.

HJ 4195 WDS 09135-6455		
Epoch	**θ (°)**	**ρ (arcseconds)**
1835.150	58.7°	18.000"
1879.850	62.4°	16.020"
1892.220	48.1°	19.968"
1915.320	65.8°	16.420"
1918.300	65.2°	16.370"
1928.370	63.0°	16.314"
1970.400	67.3°	16.284"
1991.630	68.3°	16.279"
1998.234	69.3°	16.040"
2000.010	68.5°	16.200"
2010.500	68.9°	16.200"

Figure 1: An LCO custom Meade 0.4-meter telescope with SBIG STX-6303 camera used to image the selected double stars. (Source: LCO)

Materials and Methods

Equipment

All images were acquired from Las Cumbres Observatory (LCO). The LCO telescope used was a custom 0.4-meter Meade telescope, Figure 1, with a mounted SBIG STX-6303 high-speed camera (LCO, 2018) located at SAAO in Sutherland, South Africa. This telescope has a 1.14 arcsecond per pixel resolution with a Field of View (FOV) of 19 arcminutes x 29 arcminutes. It also features a 14-position filter wheel necessary for making observations at different bands of wavelengths.

Observations

Images were scheduled at selected times to minimize the effect of air mass on the quality of the images. The far southern declination of HJ 4194 made the stars appear at low maximum altitude in the night sky from SAAO. HJ 4194 reached an estimated 40 degrees above the horizon, while HJ 4195 reached about 68 degrees above the horizon. HJ 4194 and HJ 4195 were imaged at their maximum altitude on the Barycentric Julian Dates (BJD) of 2458200.407541710 and 2458200.408888749.

A total of six images for each double star were taken: Luminance, R band, and Z band. Two images were taken at 1 second and 2 second exposures for both the luminance and the R band. Two images were taken with the z band filter and exposed for 9 and 18 seconds. Each image was analyzed and included in the calculation of the mean θ and ρ reported in Table 3. We created false-color-images of HJ 4194 and HJ 4195 using the software SAOImage DS9, shown in Figures 2 and 3, by merging the images taken with each filter into one image.

Afterward, the Mira Pro Distance and Angle auto-centroid function was used to accurately locate the center of each star by selecting the star in the image with a crosshair. Mira automatically locates the pixel with the highest ADU within a prescribed aperture to determine the stellar centroid. The exact coordinates of that pixel was identified as the first part of a line segment, shown in Figure 4. The crosshair was dragged to the second star and the process was repeated. The software automatically calculated the θ and ρ using the coordinates from each center.

Once all images were measured, we performed a statistical analysis to determine the uncertainties associated with our results. Using the data from each image, we calculated the mean, standard deviation, and the standard error of the mean for both double stars. The results of these calculations are shown in Table 3.

Since the sample size was less than 30, we estimated the population mean using a t-distribution. We creat-

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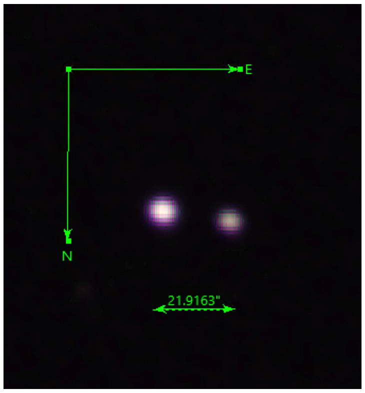

Figure 2: A false color image of HJ 4194 that we created using SAOImage DS9. The arrow represents a scale of 21.9". All six images of HJ 4194 were used to produce this image.

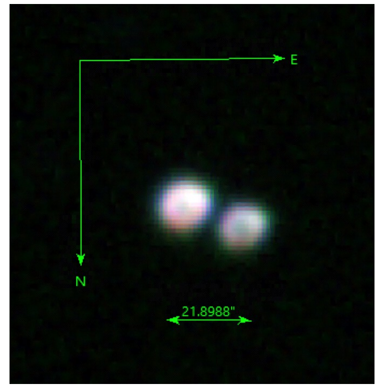

Figure 3: A false color image of HJ 4195 that we created using SAOImage DS9. The arrow represents a scale of 21.9". All six images of HJ 4195 were used to produce this image.

ed a 95% confidence interval using 5 degrees of freedom, and a t-value of 2.571. The t-value is a unit-less number which indicates the standard deviation, or the maximum or minimum deviation any possible measurement can be from the estimated population mean. The confidence interval was constructed using the formula: $x \pm t(s/\sqrt{n})$. In order to use this formula in constructing our confidence interval, and apply the central limit theorem, we used a normal probability plot to confirm that the population we were sampling from was approximately normally distributed.

Results

The astrometric measurements for epoch 2018.223 are listed in Table 4. We calculated the mean position angle of 81.6° ±0.4° for HJ 4194 with a mean separation of 18.2" ±0.1". We calculated the mean position angle 69.6° ± 0.7° for HJ 4195 with a mean separation of 16.3" ± 0.2". Each margin of error shown in Table 4 was calculated using a t-distribution with 95% confidence and 5 degrees of freedom.

Discussion

We have plotted each θ and ρ measurement of HJ 4194 using a cartesian graph tool provided by Richard Harshaw. The origin of the graph represents the primary star. Each individual data point represents the astrometric location of the secondary star in the year it was measured. The position angle and separation were used to calculate X and Y-coordinates for each measurement for each pair. The position angle is represented by the angle measured from the north axis sweeping out counter-clockwise to an individual data point. The separation is the distance in arcseconds from the origin to the individual data point. Figure 5 shows the historical data plotted with and without the data points we are assuming to have significant errors.

Each measurement is shown in chronological order

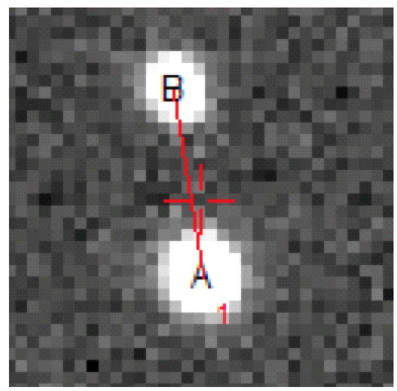

Figure 4. This is an image of the centroid function being used on Mira Pro x64. The image shows a line segment auto-centered on the primary and secondary star of HJ 4194, R-band, exposed for 1.73 sec.

Table 3: Results of our measurements.

Double Star	Measure	# of images	Mean	Standard Deviation	Standard Error of the Mean
HJ 4194	Separation	6	18.20	0.09	0.037
	Position Angle	6	81.61	0.35	0.142
HJ 4195	Separation	6	16.33	0.21	0.085
	Position Angle	6	69.55	0.67	0.275

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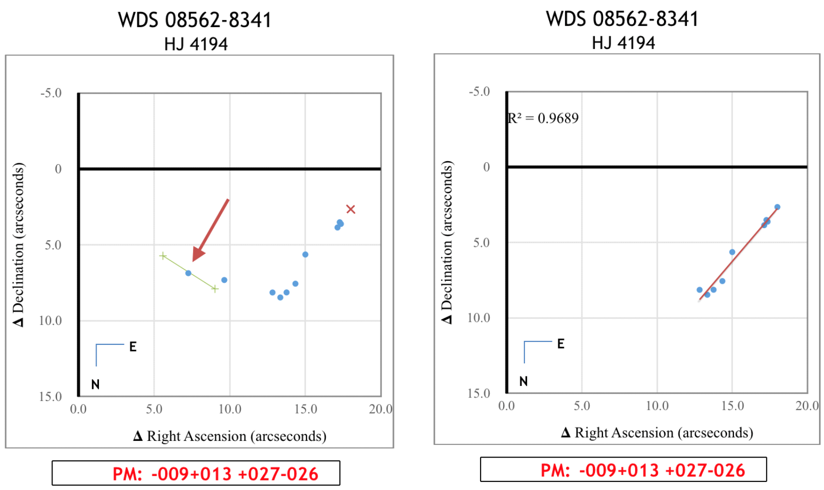

Figure 5. Plot of the historical data for HJ 4194 with errors and without.

from left to right and ends with our measurement highlighted by a red "x". The first data point was measured by Herschel and is highlighted by a red arrow. The green crosses and the line connecting them represent the two values that were averaged to produce this measurement (Herschel, 1847). Since Herschel was known for having imprecise data and his two measurements contain a very large spread in variation, we are assuming that the first data point highlighted by the arrow is also erroneous. The second data point was measured by Mr. Lawrence Hargrave with a 7 1/4 inch telescope. In the article containing the measurements by Mr. Hargrave, H.C. Russell, F.R.S., Government Astronomer, states "The positions of the other stars are approximate only" (Russell, 1892). This statement seems to suggest that the second measurement is imprecise. If we assume that these two data points are erroneous or imprecise and choose to omit them, then we can see a clear linear motion trend in the remaining data points.

Furthermore, the graph in Figure 6 shows that star B's position angle has changed by approximately 40 degrees over roughly 200 years, and appears to be increasing at a constant rate of approximately 0.2025° per year. However, if our previous assumption is correct, then the data points in Figure 6 will approach a horizontal asymptote perhaps in less than 500 years. The more distant star B becomes the position angle should appear to change less and less between 180-90 degrees.

In the cartesian graph of HJ 4195, Figure 7, the numbered data points make it difficult to discern any trend in the data. Number one was recorded by Herschel, and it is likely to have a lot of error associated with it since only one measurement was made. As we have shown with HJ 4194, Herschel had a large variation in his measurements. Number three appears to be an outlier. It was the result of a "rereduction of the Astrographic Catalogue" by the US Naval Observatory (Urban et al, 1998). In the associated article Urban states "[With respect to position] Three bands of low-precision are evident. These correspond to the Vatican, Postdam and Sydney zones" (Urban et al, 1998). The Sydney Observatory was responsible for imaging an area of the sky containing HJ 4195. Despite these issues there is a curved trend made by the remaining data points.

In addition, the pair of stars appear to be moving together in the same plane, excluding the plane in the line of sight. The pair of stars have a nearly identical proper motion. Star B also appears to show little movement in separation. This behavior suggests that star B is

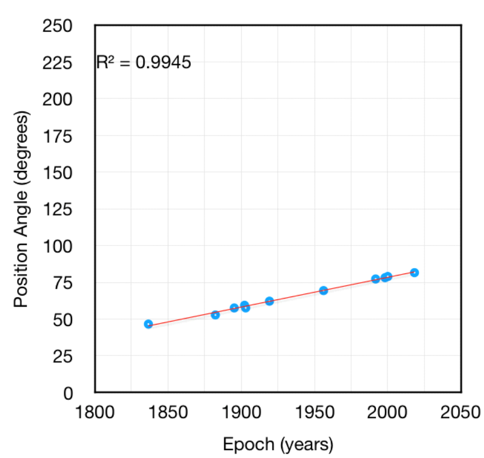

Figure 6: HJ 4194 Θ vs. Time.

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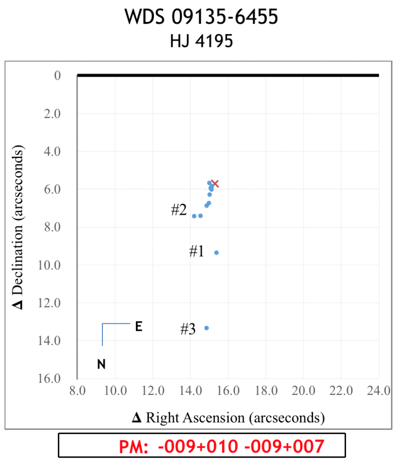

Figure 7. Plot of the historical data for HJ 4195.

possibly a common proper motion pair. However, more astrometric measurements are needed to monitor the curved trend in case this pair is a true binary star.

The distances from our Sun to each star were estimated by using parallax data and trigonometry. The European Space Agency (ESA) mission Gaia provided the parallax data for HJ 4194 and HJ 4195 (Gaia Collaboration et al, 2016). One astronomical unit (AU), or the distance from Earth to the Sun, was divided by the parallax in arcseconds providing a distance in parsecs.

Table 5 provides the parallax measurement for each component of HJ 4194 and HJ 4195, including the margin of error. Table 6 provides the minimum and maximum distance in parsecs based on the parallax data in Table 5 for each star.

The parallax data in Table 5, and the subsequent distances in Table 6, show that HJ 4194 is most likely an optical double. Star A is at a distance between 1189.63-1260.40 parsecs away and Star B is between 168.01-169.38 parsecs away from our Sun. Thus, the parallax data shows that the stars in HJ 4194 are at least 1020.25 parsecs away from each-other, and too far apart to be gravitationally bound.

Table 5: Parallax data for each star (Source: Gaia DR2).

	HJ 4194		HJ 4195	
	Star A	**Star B**	**Star A**	**Star B**
Parallax (ams)	0.817	5.928	0.798	0.605
Margin of error	± 0.0236	± 0.0241	± 0.028	± 0.0267

Table 6: Projected distance to each star in parsecs (Source: Gaia DR2).

	HJ 4194		HJ 4195	
	Star A	**Star B**	**Star A**	**Star B**
Min Dist.	1189.63	168.01	1210.65	1583.03
Max Dist.	1260.40	169.38	1298.70	1729.21

The parallax and distance data for HJ 4195 also shows no overlap in distances. Although the Gaia DR1 data showed a considerable overlap in parallax, the newly released parallax data shows that these stars may not be close to each-other at all (X. Luri et al, 2018). Any conclusion drawn from the parallax data runs contrary to those drawn from the nearly identical proper motion and the short arc which suggest these stars are physically associated.

At the suggestion of Richard Harshaw, we estimated the minimum separation between the stars in HJ 4195. First we calculated a weighted parallax using Equation 1. The weighted parallax was converted to parsecs, and finally multiplied by the last ρ measurement in the WDS. The results of this calculation show that the minimum separation by far exceeds the true separations of binary systems surveyed in the 6th orbital catalog, Table 7. The highest true separation cal-

$$PXweighted = \frac{\left[\left(1-\frac{PxAerror}{PxA}\right)PxA+\left(1-\frac{PxBerror}{PxB}\right)PxB\right]}{\left(1-\frac{PxAerror}{PxA}\right)+\left(1-\frac{PxBerror}{PxB}\right)}$$

culated was 1,707 AU, while an estimate of our double star was 23,107 AU (Harshaw, 2018).

We recommend that future research on both double stars should focus on gathering more astrometric data to confirm that Star B is moving away from Star A in HJ 4194, and to confirm that the data points observed in the cartesian graph of HJ 4195 are forming a short arc.

Conclusion

The astrometric measurements θ and ρ were successfully measured for both double star pairs. The data suggests that the secondary star in HJ 4194 is moving away from the primary, with the parallax data indicating that it is highly unlikely that the component stars are close enough to have a gravitational connection. For these reasons we have concluded that HJ 4194 is likely to be an optical double.

Table 7: Estimated minimum separation between the stars of HJ 4195.

Weighted Parallax (mas)	Distance (Parsecs)	Minimum Separation (AU)
0.702	1,424.6	23,107

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At present, we were unable to conclude the nature of HJ 4195 with the current data. The data for HJ 4195 shows that star B is showing very little change in θ and ρ. The cartesian graph in Figure 9 shows that the data points for Star B show evidence of a short arc with apparent outliers. However, the parallax data shows that there is no significant overlap in distance. The minimum separation calculated from the weighted parallax is much higher than that of known binary systems.

Acknowledgments

The Astronomy Research Seminar is an educational program which teaches students how to employ the scientific process in the field of astrometry. The seminar gives students an opportunity to collaborate, develop critical thinking, develop scientific writing skills, and present the results of their investigation to the scientific community.

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