Astrometry of Selected Binary Star Systems

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Binary stars are among the most common in the universe. Because of this, astrophysicists are interested in determining the physical properties of these systems to better understand the mechanisms of star formation and evolution. In this work, seven target binary star systems are studied and their measurements are cross-referenced with multiple databases including the binary star database, SIMBAD, and GAIA archives. From this analysis, it is suspected that two of the seven binaries are physical binaries that orbit around a common center of gravity and the rest are optical binaries (those that only appear to orbit around a common center of gravity based on their relative positions in space).

I. INTRODUCTION

Binary star systems comprise roughly half of the stars in the universe. This fact has made the study of such systems interesting to astronomers and astrophysicists who strive to determine the complex dynamics and evolution of our universe. The definition of a binary star system is that in which two stars are orbiting a common center of mass. The brighter, more luminous star is denoted as the primary star and the dimmer of the two is the secondary star (in the literature it is common to denote the stars as A and B respectively, except in the interesting case that both stars share the same brightness which is left to the discoverer to label). These should not be confused with so-called "double stars" which are stars that appear to be close to each other from our view on Earth, but are in fact not anywhere near each other in space. Loosely speaking, binary star systems can be lumped into two categories: visual and spectroscopic. Visual binaries are those that orbit at large distances from one another and move slow enough (relative to each other and background stars) that they can be discerned with the naked eye (either by telescope or binoculars) and spectroscopic binaries are those that are moving too quickly and too close together that they need be discerned using the method of spectroscopy. It is the former that we study in this paper. Double star systems were discovered as early as the invention of the telescope, as they appear to be binaries because they are close together in their positions in the sky relative to the Earth. Binary stars, However, were discovered in the mid 1700's by William Herschel, who used the mathematics and physics provided by Newton and Kepler to describe the behavior of two stars that were apparently orbiting each other. After observing these types of apparent binaries for nearly 25 years, Herschel determined that the binary stars were in fact orbiting around a common center of gravity (i.e. this was not just an effect of parallax where the position of the stars change as the Earth orbits around the Sun) and would later publish a catalog containing over 700 binary stars. After William Herschel, more and more technological advances were made in the field of astronomy and astrophysics which produced better telescopes and techniques for determining the physical properties of binary star systems.

Visual binaries compose roughly $5-10\%$ of binary star systems in the universe. If we were to make the assumption that there are roughly 1×10^{24} stars in the observable universe (assuming that all galaxies have the same number of stars as the Milky Way galaxy- 100 billion stars- and that there are 10 trillion galaxies in the universe), we can divide by two (recall that nearly half the stars in the universe are binaries) and multiply by 5%, and we're left with 25×10^{21} visual binaries that we can observe in the universe. This number gives us confidence in our ability to find visual binary stars and thereafter perform astrophysical analysis of these systems. In this work, we utilize the SBIG telescope provided by the Las Cumbres Observatory in Santa Barbara, California to take images of selected binary stars. With these images we determine the angular separation and position angle of the system and use that information to find the parallax angle. The GAIA archive was used to find the luminosity and subsequently the mass of the system. With the parallax angle, mass, and luminosity of the stars we can use Newton and Kepler's laws to unlock details about the physical properties of the selected systems. This paper is structured as follows: methods section which includes the integration times we used to perform our observations, a detailed description of how the observations and analysis were performed for each

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selected system, a results section which includes the results of our observations and measurements, and finally a discussion section on the implications of our results in the broader context of observational astrophysics.

II. METHODS

The binary stars used in these observations were found using the Binary Star Database (BSD). BSD is the world's principle database of binary (and multiple) star systems which contains data on physical and positional parameters of over 110,000 systems. This makes it an ideal source of information for finding binaries observable in the night sky during our viewing period. We restricted our search in the BSD to the following search criteria: primary star magnitude between 8 and 10, magnitude difference less than 5, and angular separations between 10 and 100 arc-seconds. With a primary star magnitude between 8-10 and magnitude difference less than 5, we can guarantee that the stars will be visible and the binary can be easily resolved by our telescope. After filtering through the database with the above criteria, we were able to select stars in the Washington Double Star (WDS) catalog and the Catalog of Components of Double and Multiple Stars (CCDM) whose physical properties were readily available online. The properties available on the BSD are the right ascension (RA), declination (DEC), angular separation (in arcseconds), position angle (in degrees), and the photometric band (the band of wavelengths in which the stars are visible). To ensure that the selected binaries were visible in the night sky during the period of observation, we took the RA and DEC values given in the BSD and plugged them into the open-source planetarium software Stellarium. This software gives users a real-time view of the night sky and allows the selection of a home location (Santa Barbara, CA was used as the home location in this work) where the night sky can be viewed in the home region. The user can also select a time and date to view the night sky and allows RA and DEC values to be plugged in to check visibility. After entering the RA and DEC values for each selected binary star into Stellarium, the target binaries were finalized and analyzed. After finalizing our targets based on their visibility with respect to the telescope and aforementioned BSD search criteria, a proposal was written to the Las Cumbres Observatory (LCO).

A. Signal to Noise Ratio

The telescope used in these observations is the 0.4 meter telescope at LCO in Santa Barbara, CA. The telescope is fitted with an SBIG STL-6303 KAF-6303E/LE charged coupled device (CCD) camera with a field of view (FOV) of 0.9×0.6 degrees and a focal length of 73 inches (both at 1 arcseconds per pixel). In order to perform the observations, a sufficient signal-to-noise ratio (SNR) and integration time were needed. In order to determine the SNR the following equation was used:

$$\frac{S}{N} = \frac{FA_{\epsilon}\tau}{\sqrt{N_R^2 + \tau N_T}}$$

where F is the point source signal flux of the telescope (in photons $s^{-1}cm^{-2}$), τ is the integration time, N_R is the readout noise, N_T is the time-dependent noise per unit time, and A_{ϵ} is the effective area. N_{τ} is given by the equation:

$$N_T = FA_{\epsilon} + i_{DC} + F_{\beta}A_{\epsilon}\Omega$$

Where i_{DC} is the dark current (in units of e_{-}/s), F_{β} is the background flux from the sky (in units of photons $s^{-1}cm^{-2}arcsec^{-2}$), and Ω is the pixel size (in arcsec). Figure 1 shows the exposure time estimation for the 0.4 meter telescope we use in this study. From this graph, an adequate SNR lies in the grey region (where the object is not over/under exposed and the shutter limit is not reached).

The effective area A_{ϵ} is given by the following:

$$A_{\epsilon} = A\epsilon Q_e$$

where Q_e is the quantum efficiency and ϵ is the efficiency of the telescope (both are dimensionless quantities).

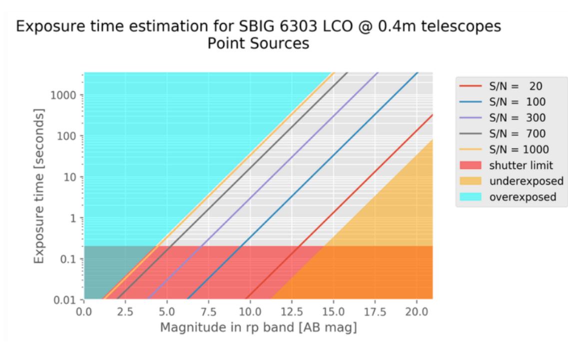

FIG. 1. Exposure time vs magnitude (in rp band) at given SNRs for the 0.4 meter SBIG telescope at LCO.

With the proper equations, we can rewrite the SNR using the more convenient form ($S_N = S/N$).

This enables us to find the integration time needed for observations, given an adequate SNR. FIG1 shows the exposure time estimation for the 0.4 meter LCO telescope at selected SNRs. For magnitudes between 8 and 10, an optimal SNR would be 300, with exposure times between 1 and 10 seconds. The integration time is the time it takes for the CCD to begin and end the photon collection (not to be confused with the exposure time, which is the time when the observatory shutter opens and closes). In order to determine this value for the final observation proposal, the SNR equation was rearranged to solve for the integration time:

$$\tau = \frac{S_N^2 N_T}{2F^2 A_\epsilon}[1 + \sqrt{1 + \frac{4F^2 A_\epsilon^2 N_R^2}{S_N^2 N_T^2}}]$$

The effective area can be solved by taking the values for the quantum efficiency of the CCD and the area of the telescope, which are reported as 0.68 (68%) and $1260cm^2$ respectively. The effective area (assuming a telescope efficiency of 0.5 (50%) is thus:

$$A_\epsilon = 428.4cm^2$$

The dark current reported by the telescope is $0.3e^-/pixel/sec$ and the pixel size (Ω) is 0.571 arcseconds. The binary stars selected are in the visible range of the photometric band, so we used the Bessel V, which has a peak wavelength of 5500 $\mathring{A}$ so the flux (F) is roughly 300 photons $cm^{-2}s^{-1}$. After assuming an ideal sky where F_β is 10^{-2} photons $s^{-1}cm^{-2}arcsec^{-2}$, we arrived at integration times of ($\tau = 60sec$) which were used for all of our source primary star observations.

B. Binary Star Analysis

After the SNR and integration times were determined, we looked for stars with a primary magnitude between 8 and 10, within the field of view of the telescope. We further narrowed our search in the BSD by requiring that we have angular separations between 10 and 50 arcseconds and magnitude differences ≤ 5. These parameters insure that the stars are indeed visual and that the stars in the binary system are discernible with a telescope. From this restriction, six binary star systems were selected from the WDS and CCDM databases. The names, angular separation, position angle, magnitude differences, and primary star magnitudes of the binaries are organized in TABLE 1. To assure that the selected binaries are indeed within the field of view of the telescope during the period of observations, the planetarium software Stellarium was used. The RA and DEC values found from the BSD were entered into the Stellarium software, which allows the user to select the location and date to view the night sky. This is useful as it allows the user to pick any date, time, and location for observations and determine what is visible in the night sky during this period.

With the visibility of the targets finalized, an observation request was sent to LCO and resulting images were shared via Google Drive. A total of 10 exposures for each target were performed; with multiple exposures we were able to calculate the average value and standard deviations of the target's astrometric properties (in this case the RA, DEC, angular separation, position angle, and magnitude difference). AstroImageJ was used to measure these properties from the resulting CCD images of each target. This software allows users to open '.fits' files as images and perform plate-solving techniques, in which the CCD is aligned with the telescope, and the axes on the target images are given in arcseconds and not in pixels (see FIG2). Our image data was delivered from LCO in a plate-solved format, allowing us to immediately perform further astrometric measurements.

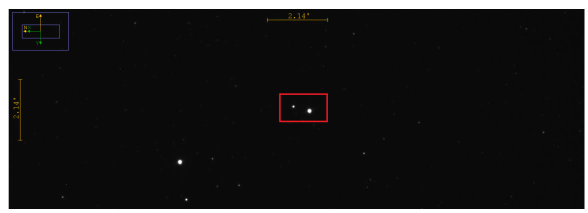

FIG. 2. Example of an image from LCO brought into AstroImageJ. The stars boxed in red is an image of one of the target binaries: WDS 20559+3206A. The axes of the image have been plate-solved, with units of arcseconds on the x and y axis of the image.

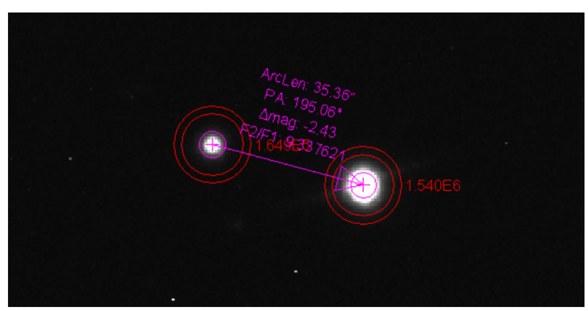

FIG. 3. Zoomed-in version of the target binary WDS 20559+3206A with astrometry measurements. The astrometry measurements yield the flux ratio, position angle (in degrees), angular separation (in arcseconds), and magnitude difference of the selected celestial objects.

One purpose of the image processing technique is to assure that the user is indeed observing the targeted binary systems. This is done by comparing the measured RA, DEC, angular separation, position angle, and magnitude difference to those values given in the BSD. Certainty in the RA and DEC values ensures that we are indeed observing the correct targets. We used a margin of error of $\leq 10\%$ between our calculated values and the corresponding values found in the BSD as the cut-off value to indicate a correct target. The other measured values will have error introduced by the efficiency limits of the telescope, CCD, and the solving technique employed by AstroImageJ.

III. RESULTS

The measurement results for each binary are organized in TABLE 2. The values recorded for all 10 exposures of each target binary are omitted here for the sake of brevity but were processed with AstroImageJ's data reduction tools. In astronomy and astrophysics, the orbital and spectral characteristics of celestial objects are often of interest. The natural next step, then, is to gather enough information to characterize the orbital characteristics of the target binaries. In order to do this, there are still some important pieces of physical information needed from the target binaries that we were not able to extract using data reduction in AstroImageJ. To find these values, the RA and DEC values of the primary and secondary stars in the binary system were used to search the archived data of the Global Astrometric Interferometer for Astrophysics (GAIA). GAIA is a European Space Agency (ESA) mission that launched in 2003 with the goal of creating the largest (and most precise) three-dimensional map of the Milky Way galaxy by surveying about 1% of the stars in the galaxy. The data from this mission is open to the public and is found online in the GAIA archives. The main source of information for this study was taken from the GAIA source2 archives, which includes measurements of luminosity, though the most recent archive (GAIA source3) does not. The archives were searched based on location in space using RA and DEC values for the primary and secondary stars. From this information, the source ID number (particular to GAIA source data) and values of interest (Luminosity, effective temperature, parallax angle, proper motion, reference epoch, RA, and DEC) can be gathered for each target binary. The RA and DEC values obtained from the GAIA source data were only used as another reference against which the RA and DEC values provided by the BSD could be compared. This further ensures that we are indeed analysing the data for the target, as the RA and DEC values from the BSD had to fall within the margin of error reported by GAIA. The results from GAIA archive searches for each star are gathered in TABLE 4. The only luminosity values that were not available in the archives was for WDS 21258+3329A and CCDM 20284+5430A. The only parameters that were available to these binaries was the RA, DEC, parallax angle, and effective temperature. As such, orbital parameters such as the mass and orbital period of the stars in the system will not be attainable. The average orbital radius (which can be determined without knowing the masses) can be used in a reduced form of Kepler's third law to approximate the orbital period of the two stars.

Before proceeding to further computations with the data gathered from GAIA, the proper motion values gathered from the GAIA archives should be mentioned. In order to determine if the binary system we are studying is indeed a physical double (and not a double star system), we need to reference the parallax angle and the proper motions. When the parallax angles overlap, we can be sure that these are indeed binary stars. The proper motion indicates how stars are moving through space, and when two stars are gravitationally bound they also move through space together. Thus, if the proper motions are close for both stars in the apparent binary, then we can be sure that these are indeed physical doubles. Using the data provided in TABLE 4, the true physical binaries from our set of targets can be determined. However, the search radius for the binary stars with the RA and DEC values of the targets is 5-10 arcseconds, so in this large range we cannot say for certain that the data taken from the GAIA archives is exactly our targets. To ensure that we were accurate in our findings, the SIMBAD database was also referenced to determine the parallax angles and proper motions. The SIMBAD database is linked directly from the BSD, so when target binaries are selected from the BSD, they are linked to 'HD ID' numbers in the SIMBAD database. This link tells us that the values recorded in SIMBAD are directly related to the targets in the BSD, providing reputable comparisons on the data that we are getting from the GAIA archives. However, because the SIMBAD database does not provide information such as the effective temperature and luminosity of the targets (important parameters for identifying orbital characteristics), the GAIA data is still required for analysis. Finally, the data in TABLES 4 and 5 were used to determine which of the targets are physical binaries. They are found as follows: WDS 21258+3329A and CCDM 20284+5430A.

We next calculated the orbital characteristics of the binaries that were found to be physical. To do this, we used the distances between the two stars (in

AU) and their masses. The distances are calculated based on simple geometry, using the parallax angle (in arcseconds, converted from milliarcseconds) to calculate the distance to the primary star:

$$D_p = \frac{1AU}{p}$$

where p is the parallax angle in arcseconds and D_p is the distance from Earth to the primary star in the binary (in parsec). Then, using the measured separation angle in radians (converted from arcseconds) we computed the distance between the two stars using:

$$D_s = D_p tan(\rho)$$

Where D_p is the distance to the primary star and ρ is the separation angle in radians. This gives a value in units of parsecs, but to use our result to find the minimum orbital period we need to multiplied the values by 206300 for units of AU. Following this, the masses can be calculated using the common mass-luminosity relationship:

$$log(L/L_{sun}) = 4.841 log(M/M_{sun}) - 0.026$$

$$M = M_{sun} \times 10^{\frac{log(L/L_{sun})+0.026}{4.841}}$$

Thus from the luminosity of the star L (in units of L_{sun} we can get the mass of each star in the binary (in units of M_{sun}. Now that the masses of the two stars in the binary are known, we determined the orbital period of the system using Kepler's third law:

$$P^2 = \frac{D_s^3}{M_p + M_s}$$

$$P = \sqrt{\frac{D_s^3}{M_p + M_s}}$$

Where P is the period of the binary orbit, D_S is the seperation distance between the two stars in AU (otherwise known as the minimum orbital radius, M_p is the mass of the primary star, and M_s is the mass of the secondary star (both in units of solar masses). The solution to this orbital period equation gives us a good approximation to the minimum orbital period in years. Should this target be a physical binary, the calculated period assumes the stars are at their maximum separation and that we are observing from a non tilted plane. The results of these computations for the two known physical binaries are organized in TABLE 6.

IV. DISCUSSION

In this project, seven candidate binary star systems were located and studied. The studied was carried out primarily by measuring the position angle and separation distance for each of the target systems. Upon dissection of the GAIA archive data made available to the public, the targets WDS 21258+3329A and CCDM 20284+5430A were found to be physical binaries (those that orbit each other around a common center of gravity), and the rest were found to be optical binaries. The archives searched and measurements performed in this study are not enough to definitively prove that the stars in this study are indeed optical or physical binaries. The data from GAIA was taken over a survey of the sky with the goal of mapping out our home galaxy, so the handling of data collected from the archives should always be cross-referenced with known values (such as the RA, DEC and parallax angles given by the BSD and SIMBAD databases). In the future, when studying these binary systems, after searching through the BSD and checking the positions with Stellarium to ensure that the stars are within the field of view of the telescope, the GAIA archives and SIMBAD databases should be referenced before the observations of the targets are requested from LCO. In this way, one can ensure that the SIMBAD and GAIA archives not only contain data pertaining to the targets but that they also contain all the necessary information to determine the minimum orbital period (i.e. luminosity, proper motions, and parallax angles) and other interesting physical characteristics of the binary systems. Furthermore, with the data already in hand, it would be easier to determine if the stars are indeed physical binaries and would reduce the need to create a list of targets to narrow down which are physical and optical binaries. This would also make it a simpler process to run through the calculations that expose important physical information about the targets.

Any future work that goes into this research will go towards collecting more data on each binary star system studied in order to confirm the claims that five out of the seven binary stars are optical binaries, and to determine other orbital parameters for the two suspected physical binaries.

V. ACKNOWLEDGEMENTS

This work has made use of data from the European Space Agency (ESA) mission *Gaia* (`https://www.cosmos.esa.int/gaia`), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, `https://www.cosmos.esa.int/web/`

`gaia/dpac/consortium`). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

This work also makes use of observations from the Las Cumbres Observatory global telescope network. We'd like to specifically thank LCO for use of their 0.4m SBIG telescope equipped with the TL-6303 KAF-6303E/LE CCD and Bessell V filter.

VI. REFERENCES

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Selected Binary	Angular Separation (arcsec)	Position Angle (degrees)	Magnitude Difference	Magnitude of primary star
WDS 20559+3206A	34.8	193	2.22	8
WDS 21258+3329A	16.3	3	2.5	8
WDS 20114+3824A	14.9	27	5	8
WDS 18488+3319A	29.8	92	2.41	8.29
CCDM 20284+5430A	13.7	13	1.5	8.1
CCDM 21563-0446A	70.9	154	2.7	8

TABLE I. Binary stars selected for analysis with given angular separation, position angle, magnitude difference, and primary star magnitude taken from the BSD.

Selected Binary	Angular Separation (arcsec)	Position Angle (degrees)	Magnitude Difference
WDS 20559+3206A	35.338	195.082	2.398
WDS 21258+3329A	16.652	1.918	3.62
WDS 20114+3824A	15.43	27.412	4.4926
CCDM 21563-0446A	67.53	151.728	3.89
WDS 18488+3319A	30.93	91.802	3.428
CCDM 20284+5430A	14.006	12.958	0.976

TABLE II. Average values of angular separation, position angle, and magnitude difference measured using AstroImageJ.

Selected Binary	Angular Separation (arcsec)	Position Angle (degrees)	Magnitude Difference
Selected Binary	Percent Error	Percent Error	Percent Error
WDS 20559+3206A	1.522440432	1.067243518	7.422852377
WDS 21258+3329A	2.113860197	56.41293014	30.93922652
WDS 20114+3824A	3.434867142	1.502991391	11.30899377
CCDM 21563-0446A	4.990374648	1.497416429	30.59125964
WDS 18488+3319A	3.653410928	0.2156815756	29.6966161
CCDM 20284+5430A	2.184777952	0.3241240932	53.68852459

TABLE III. Percent errors for the measurements of angular separation, position angle, and magnitude difference for each target binary star. The largest errors occurred in determining the magnitude difference between the stars. This is due to the systematic error in the errors due to difference apertures.

	WDS 20559+3206A	WDS 20559+3206B
GAIA sourceID	1865678199340285056	1865678199340285056
Ref epoch (yrs)	2015.5	2015.5
RA (degrees)	313.93±0.018	313.93±0.018
DEC (degrees)	32.17±0.036	32.16±0.024
PMRA (mas/yr)	9.857±0.060	4.1622±0.051
PMDEC (mas/yr)	-19.94±0.065	-1.546±0.050
Parallax (mas)	32.16±0.024	0.486±0.034
Lumonsity (solLum)	89.44133±0.065	2.7316601±0.165
	WDS 21258+3329A	WDS 21258+3329B
GAIA sourceID	1854309390838340992	1854309390838343552
Ref epoch (yrs)	2015.5	2015.5
RA (degrees)	321.45±0.020	321.45±0.014
DEC (degrees)	33.48±0.031	33.49±0.021
PMRA (mas/yr)	-12.79±0.045	-12.53±0.031
PMDEC (mas/yr)	-10.97±0.059	-10.63±0.041
Parallax (mas)	3.267±0.040	3.273±0.028
Lumonsity (solLum)	NA	1.1396158±0.014
	WDS 20114+3824A	WDS 20114+3824B
GAIA sourceID	2061682300374879488	2061688931804621184
Ref epoch (yrs)	2015.5	2015.5
RA (degrees)	302.85±0.013	302.85±0.023
DEC (degrees)	38.19±0.016	38.40±0.030
PMRA (mas/yr)	-3.797±1.546	37.70±0.050
PMDEC (mas/yr)	-6.959±1.297	118.26±0.050
Parallax (mas)	0.400±0.018	40.87±0.032
Lumonsity (solLum)	38.416412±0.127	0.38926888±0.0013
	CCDM 21563-0446A	CCDM 21563-0446B
GAIA sourceID	2670071770811953408	2669320976168683520
Ref epoch (yrs)	2015.5	2015.5
RA (degrees)	329.086±0.051	329.10±0.125
DEC (degrees)	-4.756±0.052	-4.774±0.09
PMRA (mas/yr)	2.820±0.085	62.47±0.212
PMDEC (mas/yr)	-4.366±0.093	7.980±0.181
Parallax (mas)	2.056±0.056	7.313±0.142
Lumonsity (solLum)	579.68±0.036	0.3777653±0.023

TABLE IV. GAIA archive data for each of the target stars (primary and secondary). The values that are read as NA were not available from the archive and thus are left unknown. The errors are reported from the GAIA observation runs.

	CCDM 20284+5430A	CCDM 20284+5430B
GAIA sourceID	2185013763732287104	2185013763732288256
Ref epoch (yrs)	2015.5	2015.5
RA (degrees)	307.10±0.042	307.10±0.179
DEC (degrees)	54.50±0.038	54.51±0.178
PMRA (mas/yr)	4.583±0.097	4.723±0.465
PMDEC (mas/yr)	4.002±0.073	3.593±0.408
Parallax (mas)	3.618±0.047	3.318±0.189
Lumonsity (solLum)	NA	14.214687±0.00013
	WDS 18488+3319A	WDS 18488+3319B
GAIA sourceID	2090731397562176128	2090730676007676416
Ref epoch (yrs)	2015.5	2015.5
RA (degrees)	282.20±0.021	282.21±0.016
DEC (degrees)	33.32±0.025	33.32±0.019
PMRA (mas/yr)	-64.57±0.0465	1.462±0.033
PMDEC (mas/yr)	37.95±0.050	-2.936±0.037
Parallax (mas)	10.55±0.028	0.665±0.022
Lumonsity (solLum)	3.9767435±0.004	49.19964±0.06

TABLE V. Continuation from TABLE 4.

	WDS 21258+3329A	CCDM 20284+5430A
D$_p(parsec)$	306.0912152	276.3957988
D$_s(AU)$	5089.344604	3865.361795
M$_p(solMass)$	NA	NA
M$_s(solMass)$	1.040148444	1.751823939
P (yrs)	363072.025	240317.4044

TABLE VI. Orbital characteristics for the physical binaries determined from the target binaries studied. Since the Luminosity was not available in the GAIA archives or the SIMBAD database, we had to use the original for of Kepler's third law ($P^2 = D_s^3$) to determine the average orbital period of the physical binaries.