Astrometery of Binary Star Systems

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In the following paper, we present and compare a series of measured declinations, right ascensions, and magnitudes with the official measurements of several various binary star systems. These binary star systems were observed thanks to the collaboration the Las Cumbres Observatory and it's 0.4 meter SBIG telescope in Santa Barbara, California. All observations, measurements and subsequent data analysis were conducted during the 2022-23 fall quarter at the University of California Santa Barbara.

I. INTRODUCTION

A Binary star system is one in which two stars are gravitationally bound to and in continuous orbit around one another orbiting a common center of mass. Binary stars were first observed by William Herschel in the late 1700's who utilized Newtonian and Keplarian mathematics 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 these stars were in fact orbiting around a common center of gravitational mass and would later go on to publish a catalog of over 700 binary stars.

Binary star systems comprise approximately half of all known stars in the universe, making them prime targets for cosmologists and astronomers the world over whose research and the subsequent development of new observational techniques continually contributes to our understanding of complex orbital dynamics, laws of gravitation, and the overall evolution of our universe. In addition to this, Binary stars are important to stellar astronomers as their motional data allows one to directly calculate stellar mass, effective temperature T_{eff}, and luminosity. We similarly determined these stellar parameters by taking images of our own binary star systems using the SBIG telescope through the collaboration by the Las Cumbres Observatory in Santa Barbara, California. to take images of selected binary stars. To determine the parallax angle, we used this data to find the angular separation and position. Data analysis followed suite; by using the GAIA archive to find the luminosity and stellar masses, allowing to determine a multitude of physical properties for our chosen Binary systems.

In Binary star classification the more luminous (aka "the brightest") of the two stars is denoted as the primary star (Star A) while the dimmest is donated as the secondary star (Star B) in the system. It should be noted that binary stars are entirely separate from the observational phenomenon of "double stars," a phenomenon that dates back to the earliest use of the telescope. In these cases, an observer on Earth will see stars that appear to be in orbit with one another but are in fact not anywhere near each other. Usually, this is done by measuring the separation, or angular distance, between the two stars and the position angle, i.e. the angular offset of the secondary star from the primary relative to the north celestial pole.

Once it is established that two stars are part of the same system and indeed orbit a common center of mass, the systems are than places into one of two categories: visual and spectroscopic. Visual binaries, which compose approximately $5 - 10\%$, 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 any sized telescope. Spectroscopic binaries, which are the particular binaries that pertain to this paper, are those that are moving too quickly and too close together that they need to be discerned using spectroscopy.

II. METHODS

Our binary stars and their subsequent measurements were taken from and compared using the Binary Star Data Base (BSD) . After much deliberation and some observational trial and error, we decided to evaluate only binary star systems that followed a certain search criteria, specifically that our primary star magnitudes would remain between 8 and 10 with a magnitude difference of 3 or less and angular separations between 10 and 100 arc-sec. Using this criteria allowed us to filter through hundreds of stars in the BSD and allowed us to select systems from the Washington Double Star (WDS)

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catalog and the Catalog of Components of Double and Multiple Stars (CCDM). These systems give us the added benefit of including a list of their physical properties including their declination (DEC), right ascensions (RA), and magnitudes. We then used these physical properties to ensure that our selected binaries were visible in the night sky during the time frame nights of observation. This was done by putting the right ascensions and declination's of star systems into Stellarium, a "real-time" software that allowed us to select a home location and the time in which we could view objects in the night sky, with Santa Barbara and the months of October and November of 2022 being chosen respectively. This allowed the us to further narrow our search down to our primary observational targets by eliminating any and all stars that only appear during the day in our location during this selected time frame. From here we sent our search criteria to the Los Cumbres Observatory (LCO) for image processing.

A. Finding a Signal to Noise Ratio

A Signal to Noise ratio, usually denoted S/N or S-N-R, is a measure of the strength of the desired signal relative to the background noise, which is undesired. For our observations we utilized the 0.4 m telescope, from the aforementioned Los Cumbres Observatory that was preemptively fitted with an SBIG STL-6303 KAF-6303E/LE charged coupled device camera with a field of view of $0.9 * 0.6$ ° and a focal length of 73 in (both at 1 arcseconds per pixel). For our images, we needed to estimate a proper exposure time, i.e the time that our telescopes shutter opens and closes. Looking to Figure 1, one can see the ratio between exposure time and magnitude. Here, a good S-N-R is found only in the grey region where the object isn't over or under exposed.

In order to perform the observations we need a sufficient SNR, determined by

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

as well as integration time. In the above equation, F is the telescope's point source signal flux measured in photons $s^{-1}cm^{-2}$, while τ, N_R, and N_T represents the integration time (the time it takes for the CCD to begin and end the photon collection), the readout noise, and the time-dependent noise per unit time respectively while and A_ϵ denotes the effective area. N_τ is found via the following equation:

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

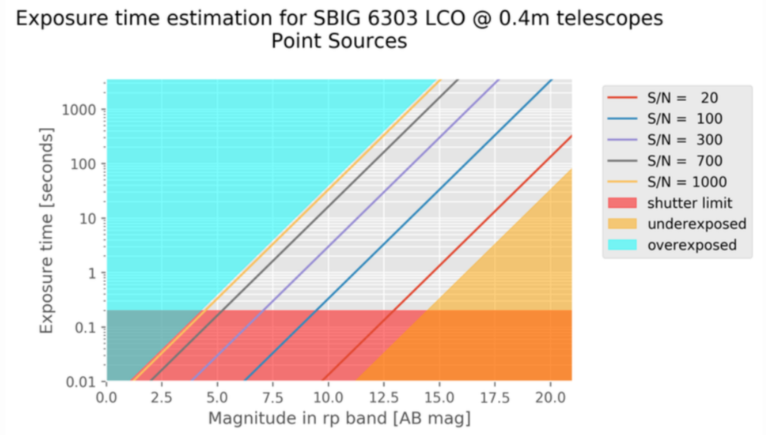

FIG. 1. Ratio between exposure time and magnitude in rp bandwidth) for a given S-N-R for LCO'S telescope.

Where i_{DC} is the dark current (e_-/s), F_β is the background flux from the sky measured in photons $s^{-1}cm^{-2}arcsec^{-2}$, and Ω is the pixel size measured in arcseconds. The effective area, A_ϵ, is dimensionless and is found via the following equation:

$$A_\epsilon = A * \epsilon * Q_e$$

where Q_e is the quantum efficiency and ϵ is efficiency of our telescope. We can plug in the quantum efficiency of the CCD of the telescope, given as (68%), and the area, given as $1260cm^2$. This gives an effective area (A_ϵ) of

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

Now we can rewrite the signal to noise ratio using the form $S_N = S/N$), which enables us to use our S-N-R to find the integration time needed for our Binary Star observations. As previously mentioned, our magnitudes are 8-10, giving us our optimal S-N-R of 300 with an exposure time that ranges from 1-10 seconds. To find the proper integration time we use the following equation, found by rearranging the S-N-R:

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

Assuming $F_\beta = 10^{-2}$ photons $s^{-1}cm^{-2}arcsec^{-2}$ we look to our dark current, given as i_{DC}= $0.3e^-/pixel/sec$ and the pixel size (Ω) is 0.571 arcsec. Our flux is $\approx 300(photons)cm^{-2} * s^{-1}$. This was found due to our stars being in the visible photo metric range as we used the Bessel V filter whose $\lambda = 5500\mathring{A}$. Plugging in these values we an integration time:

$$\tau = 60 \ seconds$$

B. Determining our Binaries

Now came the selection of our Binary Stars from the the Washington Double Star (WDS) catalog and the Catalog of Components of Double and Multiple Stars (CCDM). As mentioned earlier, a desirable magnitude for our observations lies between 8-10 with a magnitude difference of 3 or less. With our newly calculated S-N-R (S/N = 300), proper integration time ($\tau = 60$ seconds), and angular separation (10-50 arcsec), we could begin to determine our six target Visual Binaries, detailed in Table 1 with the aforementioned search criteria.

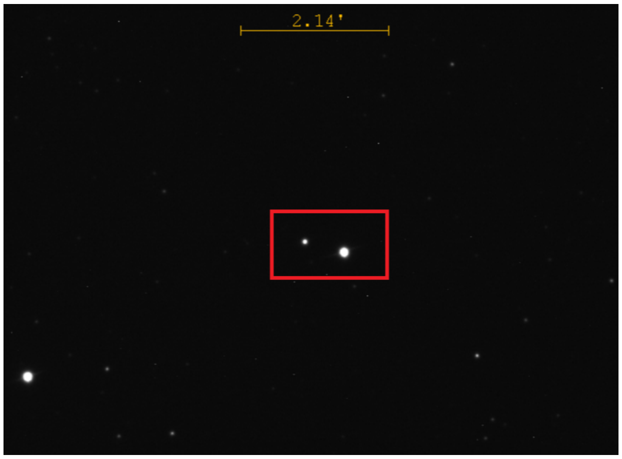

FIG. 2. Example target binary: WDS 20559+3206A. Shows an image from Los Cumbres Observatory evaluated by Astroimage.

To ensure that these Binaries lie within the view of the telescope, we utilized the software from Stellarium, a free service used as an educational tool to that renders a 3-D night sky, as well as a tool for planning observations through a telescope. By inputting our location (Santa Barbara, CA) and these stellar parameters into Stellarium we had freedom of choice regarding our pick of date, time and location for our nighttime observations. After finalizing our targets, we submitted our observation request to our Teaching Assitant: Jeonghwa Kim who then furthered our targets to Los Cumbres for processing. To ensure an accurate value and standard deviation for the stellar parameters in Table 1, each Binary Star was exposed 10 times. After receiving our data, we used the free online software Astroimage J to evaluate our target images. This allowed us to measure Angular Separation (in arcsec), Position Angle (in degrees), and Magnitude Difference, all detailed in Table 2 with an example, WDS 20559+3206A, shown in Figure 2.

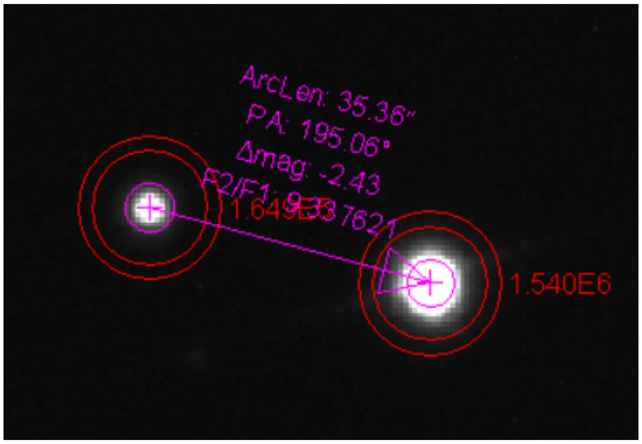

FIG. 3. The astrometry measurements for WDS 20559+3206A showing the flux ratio, angular separation, position angle, and magnitude difference.

When we first submitted our target Binaries to LCO we were unable to discern an reasonable or sizeable data that we could run through AstroImage J. The images we recived were far too pixelated to determine any physical parameters and in some cases, no binaries were visible at all. In an attempt to combat this we submitted a secondary proposal was sent to LCO, albeit this time with an uptake in our integration times. In determining our error calculations, shown in table 3, we found that the largest margin of error lied in our difference in magnitude, likely due to the aperture difference.

III. DATA AND RESULTS

Following these measurements, we can now calculate the information needed to determine the orbital characteristics of our target binaries, information the wan not discern through the use of AstroImage J.. To do this we needed to bring in The Global Astrometric Interferometer for Astrophysics (GAIA), a European sponsored database that provided astrometry, photometry, and spectroscopy for more than 1.3 billion as well as positions for additional 300 million stars in the magnitude range 3–20. GAIA also contains data for stars positions, parallaxes, proper motions, radial velocities, and luminosity, i.e brightness. We searched through the archives using the Primary and Secondary stars' Right Ascension and Declination values. We were originally going to source our data from the most recent archive, GAIA source3. However, we decided to use the GAIA source2 archives which included the luminosity measurements absent from source3. We had previously determined that we would use the luminosity to calculate the stellar mass and orbital period but unfortunately for target binaries CCDM 20284+5430A and WDS 21258+3329A, luminosity data was absent. We were however able to find the already established data for Effective Temperature (T_{eff}), Luminosity, parallax angle, proper motion, RA, and DEC and are all available for view in Table 4.

To prove that our stars our indeed Physical Binaries, and not the common phenomenon of double stars we evaluated the proper motion, described as the angular change in position of a star across our line of sight, measured in arc seconds per year. Since the parallax angles only overlap in binary stars we can see that WDS 21258+3329A and WDS 21258+3329B, CCDM 20284+5430A CCDM 20284+5430B are all but proven to be Physical Binaries. Comparing the Parallax angles of the remaining stars, one can see that difference can vastly range for system to system. The one thing that is certain is that these are in fact double stars. The only thing that can casts doubt on our established Binaries is that the search radius for the binaries with the RA and DEC values of the targets is between 5-10 arcsecs, meaning we can't say for certain if the data taken from the GAIA is accurate. To ascertain a degree of confidence, we referenced the SIMBAD database which tells us that values recorded in SIMBAD are directly related to the targets in the BSD, validating the GAIA archive data.

IV. DATA ANALYSIS

To find the orbital characteristics of a binary system, we must first calculate the distances between them which for a star is measured in Parsecs which is in itself defined as the distance of an object whose parallax equals one arc second. This gives a distance in parsecs, but to use our result to find the minimum orbital period we must covert our data results units of AU. To determine the parallax angle to calculate the distance from earth to the primary star we use the following equation:

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

which we can now utilize to find the real distance between the Primary and Secondary star we use the measured separation angle (ρ) in radians:

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

Now we can calculate the stellar masses. This is done using the mass-luminosity relationship which allows us to calculate our stellar mass (M_{star} from the luminosity (in units of L_{star} :

$$ln(\frac{L}{L_{star}}) = 4.841 * log(\frac{M}{M_{star}}) - (0.026)$$

$$M = M_{star} * 10^{\frac{ln(\frac{L}{L_{star}})+(0.026)}{(4.841)}}$$

From the masses of each star we can determine the binary orbital period of the system via Kepler's 3rd law:

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

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

Where D_S is the separation distance (AU) between Star A and Star B stars in AU with M_p and M_s denoting the stellar masses of the primary and secondary star respectively. The data for our two known physical binaries, CCDM 20284+5430A and WDS 21258+3329A, are displayed in Table 6.

V. DISCUSSION AND CONCLUSION

Overall, Binary stars are important for studying and understand stellar evolution since they are the one tool which allows us to determine the masses and luminosity for stars independent of their distances. Had we ascertained more time and resources, we could further add both proven and disproven binaries to our list by expanding our target systems.

To summarize, we sought to study and evaluate a variety of Binary Stars by measuring their Angular Separation, Position Angle, Primary Star, Magnitude, and Magnitude Difference by running the LCO data through AstroImage J. Doing this allowed us to calculate the parallax angles, proving that star WDS 21258+3329A and CCDM 20284+5430A were indeed Binary Systems. Utilizing the GAIA and SIMBAD archives, we further validated our calculations as these databases contain already pre-established stellar data for our target star. Then we caculated the orbital characterises for these stars, including Solar Mass, Separation Distance and orbital period as seen in Table 6.

VI. REFERENCES

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Selected Binaries	Angular Separation (arcsec)	Position Angle (degrees)	Magnitude Diff.	Primary Star Magnitude
WDS 20559+3206A	34.8	193	2.22	8
WDS 21258+3329A	16.3	3	2.5	8
WDS 18488+3319A	29.8	92	2.41	8.29
WDS 20114+3824A	14.9	27	5	8
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. Using Astroimage J, we measured the above angular separations, position angles, and magnitude differences for our six selected Binary Systems.

Selected Binaries	Angular Separation (arcsec) percent error	Position Angle (degrees) percent error	Magnitude Diff. 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. Our percentage error calculations, shown here, found that the largest margin of error lied in our difference in magnitude, likely due to the aperture difference.

	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)	321.450.020	321.450.014
DEC (degrees)	33.480.031	33.490.021
PMRA (mas/yr)	-12.790.045	-12.530.031
PMDEC (mas/yr)	-10.970.059	-10.630.041
Parallax (mas)	3.2670.040	3.2730.028
Lumonsity (solLum)	NA	1.13961580.014
	WDS 20114+3824A	WDS 20114+3824B
GAIA sourceID	2061682300374879488	2061688931804621184
Ref epoch (yrs)	2015.5	2015.5
RA (degrees)	302.850.013	302.850.023
DEC (degrees)	38.190.016	38.400.030
PMRA (mas/yr)	-3.7971.546	37.700.050
PMDEC (mas/yr)	-6.9591.297	118.260.050
Parallax (mas)	0.4000.018	40.870.032
Lumonsity (solLum)	38.4164120.127	0.389268880.0013
	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
	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 IV. Already predetermined data for our target Binary Systems from GAIA archive data, courtesy of the European Space Agency. The middle column contains the GAIA data our primary star while the farthest right column showcases data as it pertains to the secondary. All values labeled as N/A were absent from the archive.

	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

TABLE V. Cont. of 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. Calculated orbital characteristics for our proven physical binaries.