Double Stars and Stellar Binary Systems: An Astrometric Analysis

Introduction

Double stars are a fascinating phenomena in astronomy, their uniqueness and uncommon nature standing out amongst the much more numerous single stars (Lada, 2006). Double stars divide into two categories, the optical double star and the binary star system.

Optical double stars are a pair of stars that are not bound to one another gravitationally. These stars only look to be connected to another from our vantage point. Binary star systems occur when two stars, a primary star and a secondary star are bound by gravity, orbiting around a shared center of mass. In order to be classified as a binary system, these pairs of stars must have a binding energy under zero. Any energy above zero and the pairs are classified as double stars (Letchford et al. 2021).

These systems are fairly uncommon, as they only make up about one third of the stars in the Milky Way (Lada, 2006). Observed long before they were discovered, William Herschel was the first to conclude that many of the stars he studied were in fact gravitationally bound and orbiting one another (Herschel, 1803). In the past 200 years since then, our understanding of binary stars has grown as they have been used to understand other aspects of astronomy.

There are various techniques available in order to identify binary stars, though astrometric and photometric techniques will be our main focus. Astrometric techniques involve observing the change in position over time. They detect non-uniform motion of the stars when observed, a "wobbling" motion is present in one of the stars, implying that the star undergoing slight perturbation is being affected by the gravity of another object (Halbwachs et al. 2022).

Photometric techniques are used to identify eclipsing binaries. These binaries occur as one star overtakes the other relative to our line of sight, causing the light to fluctuate. This is generally found through a light curve analysis (Bruton).

Binary systems are incredibly important to research today. In particular, binary systems impact the understanding of stellar formation models. This furthers our understanding of the dark matter hypothesis versus the modified Newtonian dynamics hypothesis (Letchford et al. 2021).

Binary stars are also some of the few ways that a mass of a star could be obtained, since this requires gravitational interactions between two objects.

In this paper, we aim to do an astrometric analysis of three pairs of double stars. Two are proper binary systems, the other an optical binary. Our main goals are to first use astrometric methods to calculate the position and separation angles of each pair of stars. We will compare with previously created orbit plots. Once it is confirmed that our data supports the current expected positions of each double star, we must obtain our own apparent magnitudes and utilize this data in order to attempt to confirm the orbital periods of our two binary systems.

Materials and Methods

Preliminary observation data was obtained in late April and mid May, using 0.4m telescopes operated by Las Cumbres Observatory (LCO) in Tenerife, Spain and Mauna Kea, Hawaii. The telescopes were equipped with SBIG STL-6303 cameras with filters. In order to increase the chances of obtaining clear data, we were advised to use the Bessel B, Bessel V and SDSS g', filters. Our integration time was kept short at 1-2s.

Initially, we planned to confirm our stellar systems were binary stars using astrometric or eclipsing methods. Limited by time and resources, we created the following parameters to obtain workable data.

The stars' must measure around 7-11 in magnitude, with the differences in magnitude between the primary and secondary star less than or equal to 2. Stars below 7 in magnitude were much too bright for our telescope, while stars over 11 were in danger of being too noisy or dim. Ideally, the angular separation between primary and secondary stars was to be 10-100 arcseconds. Originally, the period of the systems was to be less than, or equal to two weeks. This short period would have allowed the systems to visibly change in our short time period. In addition to this, it was essential to ensure the targets were visible using the LCO's visibility calculator.

Initially, we found the optimal exposure time for our Bessel B, Bessel V and SDSS g' filters using the LCO's exposure time calculator and estimation graph on the observatory's website. Following that, a calculation of signal to noise ratio(SNR) was done using the following equation:

$$\frac{S}{N} = \frac{FA_e\tau}{\sqrt{N_R+\tau N_T}}$$

It was determined that the signal to noise ratio with one second of integration time would be $\frac{S}{N} \approx 234.4$

As the quarter progressed there was too little time to obtain more data and properly do a light curve analysis so it was decided that an astrometric method of confirming binaries would be utilized. To achieve this, a mix of historical data coupled with our own data was thought ideal. This adjustment allowed us to choose binary systems with longer orbital periods, increasing the number of systems that fit our other parameters. Eventually, this led to problems and forced us to adjust our research and analysis.

To adjust, we decided to use Stelledoppie's projected position and separation angle and compared the current data to see if our systems were in the right spot in 2023. In addition to this we decided to find the orbital period of our two binary systems.

The target binaries were STF 2128, STF 2398 AB and HEI 9004 AD. STF 2128 is a binary system with an orbital period of 2294 years with an angular separation of 12.11" and a magnitude of 8.76 for the primary and 10.34 for the secondary. STF 2398 AB is another binary system with an orbital period of 408 years, an angular separation of 11.4 " and a primary magnitude of 9.11 with a secondary magnitude of 9.96. Our last pair of stars, HEI 9004 AD was only a visual binary, and thus not ideal for our project. Due to this, this pair will be mentioned but not focused on.

After a semi-successful, but largely failed attempt to graph the orbital period of STF 2128, our original goal to plot the orbits of our selected binaries became unfeasible. Any attempts to do so showed what could have been a part of the systems' trajectories, but nothing larger than that. This is due to the binaries' long orbital periods. Although the long periods meant the systems had large separation angles, it meant we could not see any change in their positions in such short time periods. Since the other two systems were similar, we had insufficient historical data and could no longer analyze and confirm or deny whether they were indeed binary systems using that astrometric method.

Data and Analysis

Image of STF 2128 taken with the Bessel B filter (fig. 1) with the projected orbital of the system below. A red line connects the primary star to the current, 2023 position of the secondary star (fig. 2). A simple visual comparison of the system with the red line indicates that the secondary star seems to be in its expected 2023 position. A more concrete analysis will be done to confirm this.

Figure 1: System STF 2128 taken with Bessel B filter. Secondary star is the smaller of the two (LCO)

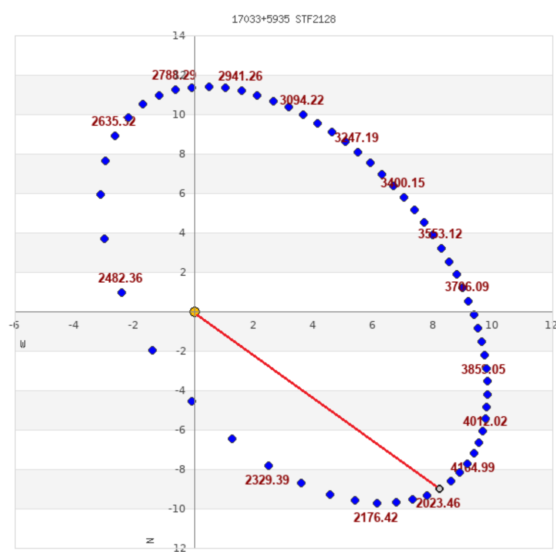

Figure 2: Projected orbit of binary system STF 2128. Line connects primary and secondary stars in their current position. North is downwards as East points rightwards (Stelledoppie).

The following is an image of STF 2398 AB, taken with a SDSS g' filter (fig. 3). As before, a visual comparison of the system and the red line connecting the two stars in the plotted orbit(fig. 4) suggests the secondary star seems to be in its expected 2023 position (fig. 4). As with STF 2128, this will be confirmed more concretely.

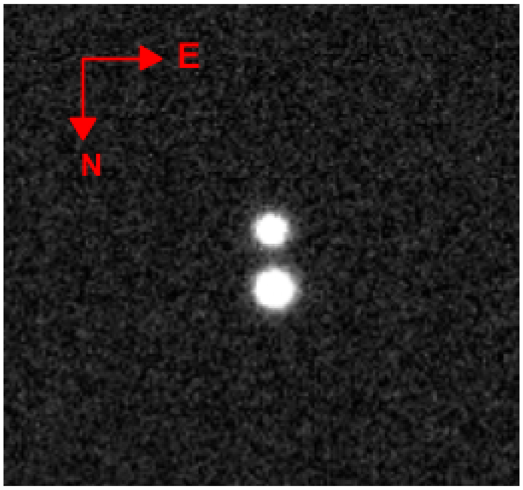

Figure 3: System STF 2398 AB. Image taken with SDSS g' filters (LCO).

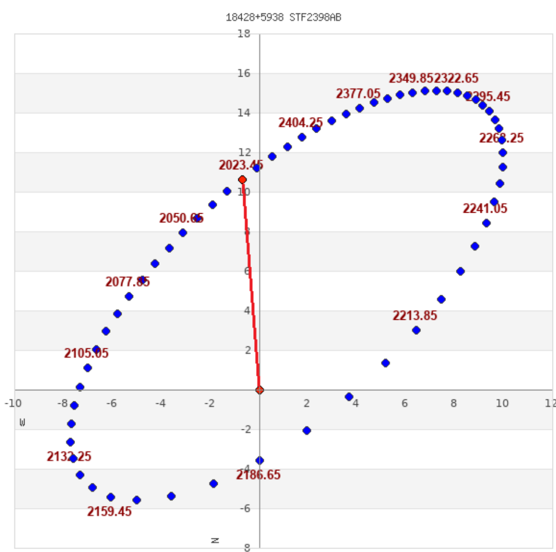

Figure 4: Projected orbit of binary system STF 2398 AB . Line connects primary and secondary stars in their current 2023 position (Stelledoppie).

Figure 5 shows the double star HEI 9004 AD. As demonstrated in the image, these two stars are far apart. This suggests this is a visual binary, not gravitationally bound, therefore containing no historical and projected orbit. It is interesting to note the distance between the primary and secondary star of HEI 9004 AD. Compared to STF 2128(fig 1) and STF 2398 AB (fig 3) they seem incredibly far apart.

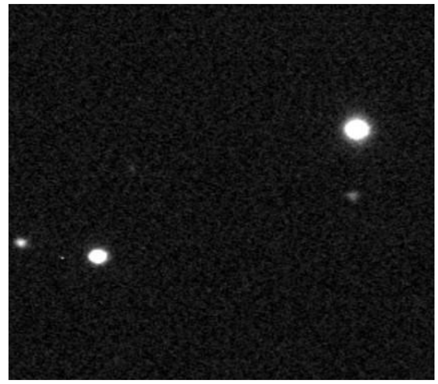

Figure 5: Double star HEI 9004 AD. Image taken with the SDSS g' filter.

In order to get the separation angle (ρ) between the two stars in the systems and the position angle (θ) of primary and secondary stars, the following equations were used.

$$\rho = 3600\sqrt{(dRA)^2 + (dDEC)^2}$$

$$\theta = 180\ (tan(\frac{dRA}{dDEC}))$$

Where:

$$dRA = 15(RA_1 - RA_2) \times cos(DEC_2)$$

$$dDEC = DEC_1 - DEC_2$$

Here, RA_1, RA_2 are the right ascension of the primary and secondary star and DEC_1, DEC_2 are the declination of the primary and secondary star. If dRA or $dDEC$ is negative, 180° is added to the position angle in order to bypass our calculator's $arctan$ bug. This had to be done to the position angle of STF 2398 AB and HEI 9004 when using data from the Bessel V filter.

For each system, we obtained the position and separation angles from Bessel B, Bessel V and SDSS g' filters using AstroImageJ software. An average of those angles were taken in order to get the data of Table 1. Note how much larger both angles of HEI 9004 AD is compared to our true binaries.

Systems	Separation Angle ρ (arcsec)	Position Angle θ (degrees)
STF 2128	11.656	43.920
STF 2398 AB	11.201	181.087
HEI 9004	109.77	334.93

Table 1: Calculated data of all three pairs of stars. Averages of calculated position and separation angles of Bessel B, Bessel V and SDSS g' filters

Systems	Separation Angle ρ (arcsec)	Position Angle θ (degrees)
STF 2128	12.17	42.6
STF 2398 AB	11.4	182.5
HEI 9004	109	335

Table 2: Catalog data of all three pairs of stars (Washington Double Star Catalog).

As shown, our calculated position and separation angles line up with catalog data. This confirms our earlier visual comparisons, STF 2128 and STF 2398 AB are currently in their rightful position according to their plotted orbits (fig 2, fig 4).

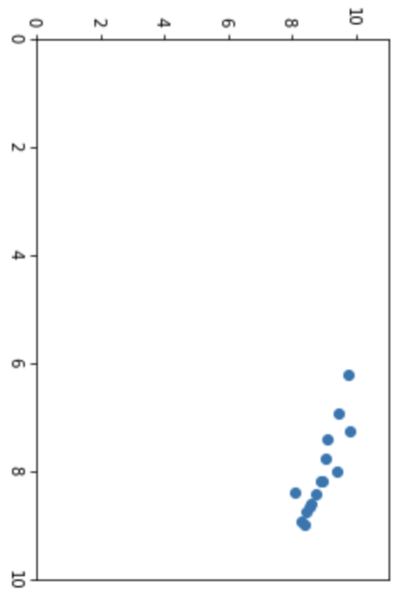

Figure 6: Plot of segment of STF 2128's orbit.

Figure 6 illustrates a plot of a section of STF 2128's orbit. Compared with figure 7, our plot follows that of Blanco's group closely. This confirms

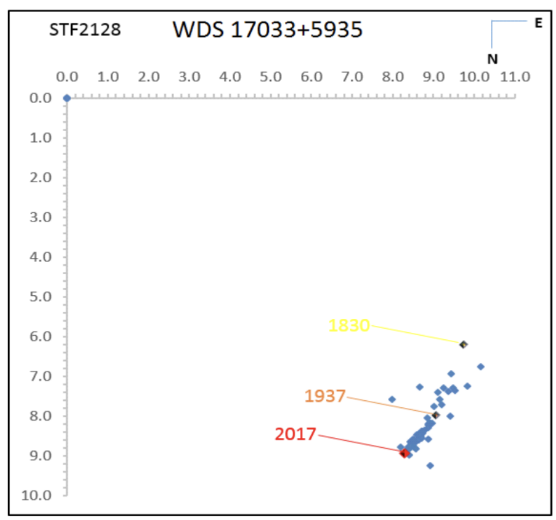

Figure 7: Orbital plot of historic data and most recently found point (Blanco et al. 2018)

To obtain the magnitudes for each of our pairs of stars, we processed five images for each filter, then obtained the magnitudes under our three separate filters using the Star

Atlas. These magnitudes were averaged out to get the figures in table 3.

System	Magnitude A (Average)	Magnitude B (Average)
STF 2128	8.76	10.34
STF 2398AB	9.11	9.96
HEI 9004	7.91	9.55

***Table 3**: Magnitude averages of three pairs of stars. A is the primary star and B the secondary star.*

	% Error (A)	% Error (B)	Std. Dev (A)	Std. Dev (B)
STF 2128	10%	11%	1.926	2.046
STF 2398AB	3.49%	3.70%	0.201	0.212
HEI 9004	0.09%	4.06%	0.806	0.222

***Table 4**: Percentage error and standard deviation of our average calculated magnitude*

After all this data was obtained, it was possible to obtain the orbital periods of systems STF 2128 and STF 2398 AB orbital periods, using Kepler's third law.

$$T = \sqrt{\frac{4\pi D_s^3}{G(M_A + M_B)}}$$

Where D_s is the distance between the two stars and M_A, M_B are the masses of the primary and secondary stars, respectively.

The distance between the two stars was obtained using our calculated separation angles (ρ) in radians and the distances from earth d_e in a.u.

$$D_S = d_e \tan(\rho)$$

Our magnitudes from table 3 were used in order to find the absolute magnitudes using the following formula:

$$M_{abs} = m_\star - 5\log(\frac{d_e}{10})$$

From there finding the luminosities of the primary stars and using the mass-luminosity relationship to get masses.

$$\frac{L_\star}{L_\odot} = 10^{0.4(4.85 - M_{abs})} = (\frac{M_\star}{M_\odot})^{3.5}$$

Once calculated, our orbital periods (T) were:

	Catalog T	Calculated T
STF 2128	2294 y	3512.2694y
STF 2398 AB	408y	239.22 y

Table 4: Orbital period, our calculated vs. catalog

Table 4 indicates that our calculated orbital periods greatly differ from the system's catalog orbits. The use of the distance between the two stars was not ideal, and we believe our values would have been closer if we had used the semimajor axis of the systems instead.

[Data and codes]

Conclusion

In conclusion, our calculation of binary systems STF 2128 and STF 2398 AB position and separation angle suggest that they are indeed following their previously plotted orbit. Unfortunately, one data point cannot confirm their identities as binary systems, but their current position and separation angles does line up with previous evidence identifying them as such. These systems are not optimal for short term astrometric study with limited resources. Due to their long periods, they will hardly fluctuate and "wobble," over time. I would not suggest further study into these systems within these constraints.

The calculated orbital periods were not optimal. While using the semimajor axis instead of the distance between the stars may allow us to achieve a closer orbital period, I believe that the orbital periods required an over reliance on catalog data again because the systems characteristics were too limiting when coupled with our resources.

HEI 9004 AD provided an interesting look into the star, and allowed for an interesting way to gauge just how different the two types of binaries could be.

If this project could be redone, I would implement a number of improvements in order to get more relevant and effective data. My biggest change would be to increase our preparation, planning and research at the very beginning of the class. Eager to obtain data, my group and I decided on the ideal parameters of our systems but did not map out what kind of methods of stellar binary identification we wished to use and how we would analyze our data once we obtained it. Due to this, we did not know our next step, and had to adjust and change our project more than I preferred.

To prevent this, I would choose binary star systems with periods that were massively reduced. Had we restricted our systems in this way, we likely could have done a light curve analysis. If we still wished to plot the systems' orbits, we should not have assumed that we would have enough historical data to analyze the system via astrometry. This assumption was due to inexperience, while the systems did have what seemed a considerable amount of data to the group, they did not. It is likely that our advisors would have pointed out our mistake if we had checked in with them to make sure of this.

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