Eclipsing Binary Star System

13 June 2023

I Introduction

The same way that the moon rotates around the earth, and the earth rotates around the sun, so do other systems rotate around each other. A system of two stars in rotation around each other constitutes a binary star system. This system contains two stars which orbit around each other in accordance with a gravitational pull towards the center of their mass. Depending on angle of viewing, amidst other things, an eclipse between the stars can be observed. One way to observe this eclipse is to measure the change in magnitude as one star crosses over the other[1]. When this happens, the orbiting star blocks some light from the other star, and allows measurements to be made surrounding orbit, mass, etc. These are called eclipsing binary stars.

Historical Background

The amount and variety of binary star systems is appreciably large. In fact, up to 85% of stars are part of binary systems, or higher [2]. Of these systems, there are multiple classifications of binary stars. These include visual binaries, spectroscopic binaries, eclipsing binaries, astrometric binaries, and 'exotic' types. Eclipsing binaries are defined by their ability to be observed through their apparent magnitude, as mentioned earlier. The first detection of an eclipsing binary was "Algol, β Perseus", or "Demon Star" [3]. This discovery was made by Goodericke in 1782, following the first binary star in general made by J. B. Riccioli around 1650, not long after the construction of the first telescopes. At first, people (such as I. Newton) thought that the stars could be part of these binary star systems, but this idea was written off due to lack of evidence. Instead, ideas such as differential parallaxes were considered, but disproven. In demonstrations based on binary stars, W. Herschel showed this idea of mutual attraction within a physical system, which is regarded as the first observational evidence of Newton's Law of Gravitational Attraction [4].

Importance

A visual binary star can be analyzed through a light curve. By taking the apparent magnitudes of the system over a time interval, and plotting these values as a function of time, the eclipse of the system can be found. In a full set of data, a light curve should show the primary eclipse, of the secondary star overlapping the primary star, and the secondary eclipse, of the primary star overlapping the secondary star [3]. By creating a light curve showing these peaks in apparent magnitude, the orbit of the system reveals valuable information about the size of the stars, and the masses [5]. In a more general sense, visual binary stars also represent a simple, yet complex system of a mutual gravitational pull towards a shared central mass. It is interesting to utilize the Gravitational force equation without one mass being large enough to neglect the other, as is the case with how we treat the gravity between Earth and our daily objects.

II Instrumentation and Methods

Choosing our Star System

Of the varieties of binary star systems, an eclipsing binary star system has a lot of practical benefits, in the sense that we would only need to calculate apparent magnitudes as a function of time, and avoid the distortion of masses that occurs in other systems. In order to choose an eclipsing binary star system, we first had to decide what requirements we were looking for, based on our parameters. In terms of instrumentation, we could request data through the Las Cumbres Observatory, where we had access to filters with wavelength centers ranging from ~3000-10,000 Å [6]. We also had a time constraint, as our data collection needed to take a maximum of a couple weeks. In an effort to get the most concentrated and full set of data given these constraints, we decided to find a star system which was within a magnitude of 9-12 kmag, with a period of 24 hours or less. This way, the magnitude of the star system is in the right range of magnitude for the instruments we were using, and the time period is one which allows us ample time to analyze the data, and request more if needed. In order to find this star system, we used the website 'Kepler Eclipsing Binary Catalog - Third Revision' [7], and gathered some potential star systems. Once we had some options, we had to take visibility into account. Using the 'Visibility Tool' on the Las Cumbres Observatory website, we entered the target coordinates to see the visibility on the LCO network for both seasonal and daily visibility [8]. Upon fulfilling all of the previous criteria, the star system we decided on has KIC number 3833859, with an RA of 285.8739 and a DEC of 38.9039 [7].

Methods

In order to obtain images of our star system, we sent in a request (through the TA) who sent the request to the Las Cumbres Observatory. Using the same visibility feature on the LCO website [8], we found that the best filter for our star system is the SDSS g' filter. This is a standard filter on LCO's 2, 1, and 04 meter telescopes. The wavelength center associated with this green filter is 4770 Å. By choosing this filter, we were able to boost contrast between the wavelengths coming from our star, and from the background noise. We added this filter to our request sheet, along with the RA and DEC. We requested 4 exposures, with an integration time of 12 seconds. We chose to get 4 shutter photos so that we could average a magnitude over more than just one photo, and get more accurate magnitudes. Lastly, we listed that the expected period of our star system was around 9 hours, within which we wanted 5 sets of photos. We received data from around 3 hours, and requested more data with the same filter, but over the course of 24 hours.

Our methods for analyzing our data are as follows. We ultimately had two sets of data- one with closer spaced intervals, but a shorter overall period, and one with a longer interval with data spaced far apart. Specifically, we had a set of data that contained 5 points with 4 photos each over the course of around 3 hours, and a set of data that contained 14 points with 2 photos each over the course of 24 hours. We received these photos in .fitz format, and converted them all to .fits files. We used the application 'SAOImage DS9' to get the timestamp of each photo. In order to get the most accurate time stamp, we used the start time for the first photo in a set point, and the end time for the last set point and averaged the time. We obtained values of uncertainty for our time values by taking the smallest unit the timestamp of each photo went to.

Each photo we received came in pair with its raw image and its BANZAI processed image. We chose to use the BANZAI processed images as opposed to the raw images for their enhancing calibrations which will be discussed further in instrumentations.

For each data point, we utilized the application 'Astroart 8' to locate our star system, combine each photo in set, and obtain magnitude values. This meant using the Star Atlas tool on Astroart to locate our star. We relied on The European Space Agency's 'GAIA' map to locate our star. We used the brightest reference stars in our photos to match our photos with GAIA's map, which provided us with coordinates for our photo. This way, we could find our star based on its known coordinates. Once we located our star, we aligned and combined all photos in a data point together to get an average magnitude. At first, we planned on manually averaging the pixel luminosity from the cluster of pixels that composed the star [Figure 1]. Ultimately, we found it to be more consistent to rely on Astroart's magnitude for our star instead.

Once we had our time stamps and magnitudes, we were able to make our light curve. As we had two sets of data, we created two light curves, one a more zoomed in (time-wise) version of the other. I chose to use python to plot these graphs via Jupyter Notebook on Anaconda. I exported a tsv file with the x column representing the timestamps in units of seconds, shifted so that the first data point was at 0 seconds. The y column represented the apparent magnitudes for each timestamp. I imported this tsv file into my code, along with the packages numpy and matplotlib.pyplot. I also included the uncertainty for each column using the following formula for signal to noise ratio:

$$\frac{S}{N} = \frac{FA_{\varepsilon}\sqrt{\tau}}{\left[\frac{N_V^2}{\tau} + FA_{\varepsilon} + i_{DC} + F_{\beta}A_{\varepsilon}\Omega\right]^{1/2}} = \frac{FA_{\varepsilon}\sqrt{\tau}}{\left[\frac{N_V^2}{\tau} + N_T\right]^{1/2}} = \frac{FA_{\varepsilon}\tau}{\left[N_R^2 + \tau N_T\right]^{1/2}}$$

Where the uncertainty for the magnitudes are $\frac{1}{\left(\frac{N}{S}\right)}$

N_R : *Readout noise* (e^-)

N_T : *Time dependent noise per unit time*

τ : *Integration time* (s)

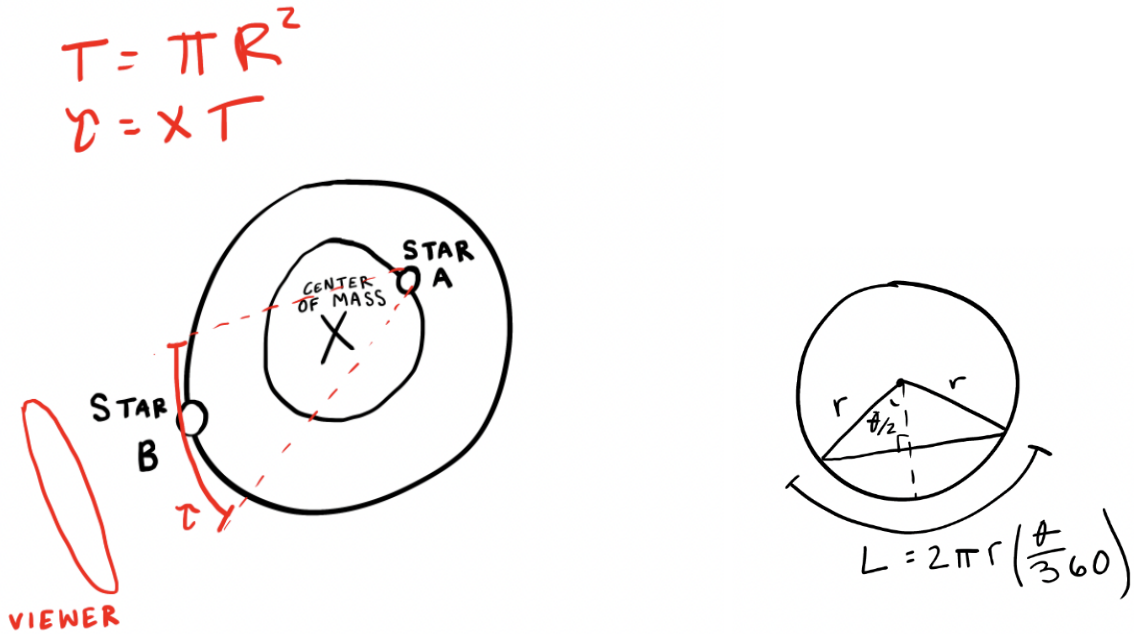
F : *Point Source Signal Flux on Telescope* $(photon/(s \cdot cm))$

A : *Telescope Area* (cm^2)

Ω : *Pixel Size* $(arcsec)$

i_{DC} : *Dark Current* (e^-/s)

From these light curves obtained, we were hoping to piece together a general orbital period for the eclipsing binary stars from quantitatively observing the rise in the light curve. However, there are too many missing factors which we would need and do not have to be able to do this. Essentially, we are getting a timeframe for one star completely overlapping the other, but we would need to know speed, mass, radius of separation, or other things to be able to plug this into an equation. Instead, we focused on finding the transient moment of the eclipse; being able to identify it from our data and make assumptions based off of it. Further, using the known orbital period as reference, I found what fraction of the full orbit my data constituted, and pieced things like field of view together. Figure 10 shows a drawing of how this would work.



[Figure 10] Schematic diagram of what my data would represent. Calculating the field angle that we can view the star.

Lastly, in an effort to expand past our goal of identifying the transient event from a light curve, we wanted to see the effect of different filters on our image data. Our goal was purely to provide supplemental data to our project, in the form of qualitative analysis between the filter our light curves were based off of, and other options of filters. In particular, we requested data for the red and blue filters. These corresponded to wavelength centers of 6407Å and 4361Å respectively. The images can be found below in Figure 5 and Figure 6, respectively. Doing this additional step contributed to our main goal by providing us with some insight into the effect that our filter choice may have had on our final data sets.

Instrumentation

The telescopes used to take the images of our photos are from the Las Cumbres Observatory. They have 25 telescopes around the world, which allows data to get moved around to different sites, providing fuller and more consistent data. These 25 telescopes operate as a 'single instrument'. These instruments were all built by LCO and work day and night. The 0.4 meter diameter telescopes in particular are modified Meade telescopes with the following properties. The mounting is composed of 'Meade 16-inch (40cm) RCS tube and 3-element optics, mounted in LCO equatorial C-ring mounting', while the optics operate with 'Primary, secondary and Corrector plate (Meade) with LCO focus mechanism driving corrector plate/secondary'. The cameras on this telescope are the SBIG STL-6303, formatted with a 3Kx2K 9-micron and a cycle time of 14 seconds [9].

The BANZAI processed images are a result of raw images being processed through LCO's BANZAI pipeline, which comes from image processing algorithms from the 2014 Global Supernova Project team. It is coded in Python and runs automatically. The calibrations which it performs on raw images are: "Bad-pixel masking, Bias subtraction, Dark subtraction, Flat field correction, Source extraction (using SEP, the Python and C library for Source Extraction and Photometry), and Astrometric calibration (using astrometry.net)" [10].

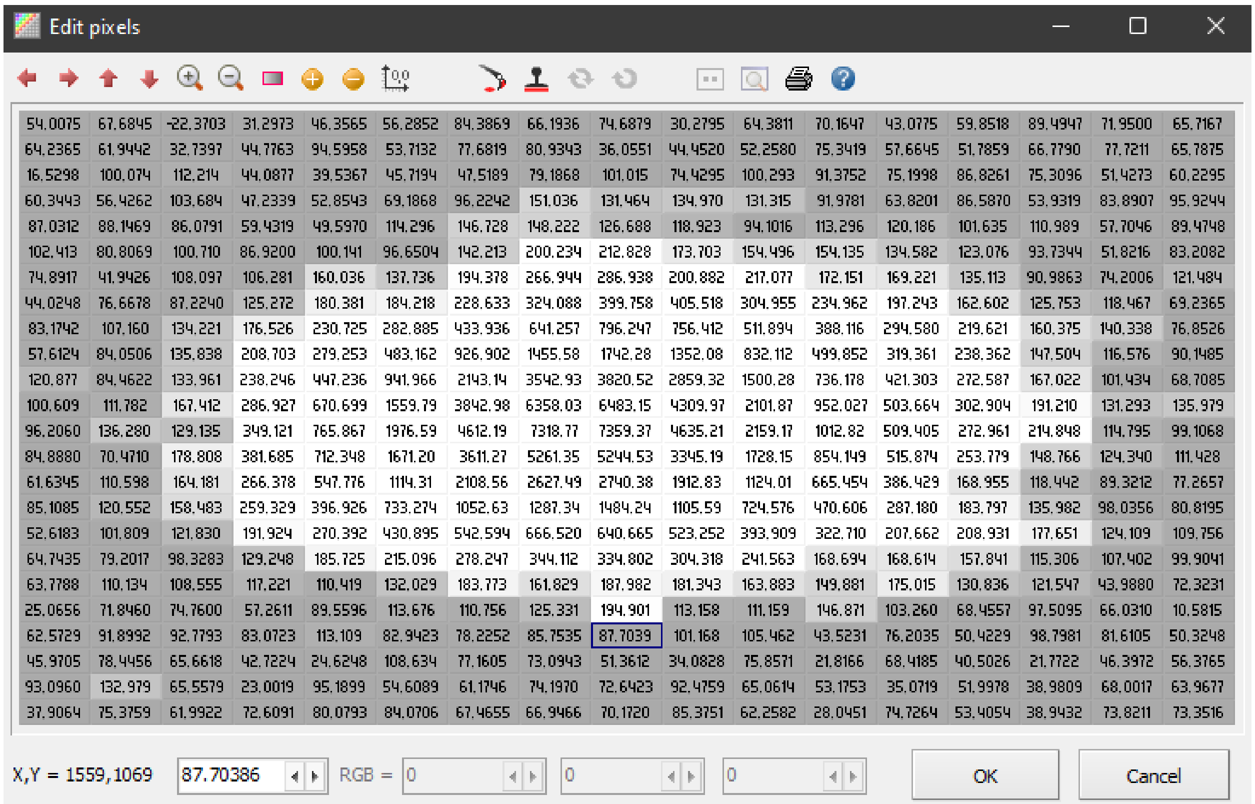
III Results

Summary of Images

We received two sets of data; one with 5 data points each containing 4 photos over 3 hours (Data Set 1), and one containing 14 data points each containing 2 photos over 24 hours (Data Set 2). Photos from Data 1 looked similar across data points, while photos from Data 2 varied as a result of some photos being taken during the day. Discrepancies within each Data Set included receiving raw versus BANZAI processed images, which we overcame by being consistent in using the processed set of images. In addition, photos of the red and blue filter photos are shown for contrast against our dominantly green filter data.

[Figure 1] Green filter, Data Set 1, unprocessed. Labeled with the star system we measured, this is a solo image, not combined with other photos at the same time. This is the raw version of Figure 2. The only edits done involve adjusting contrast and brightness to more easily make out the stars.

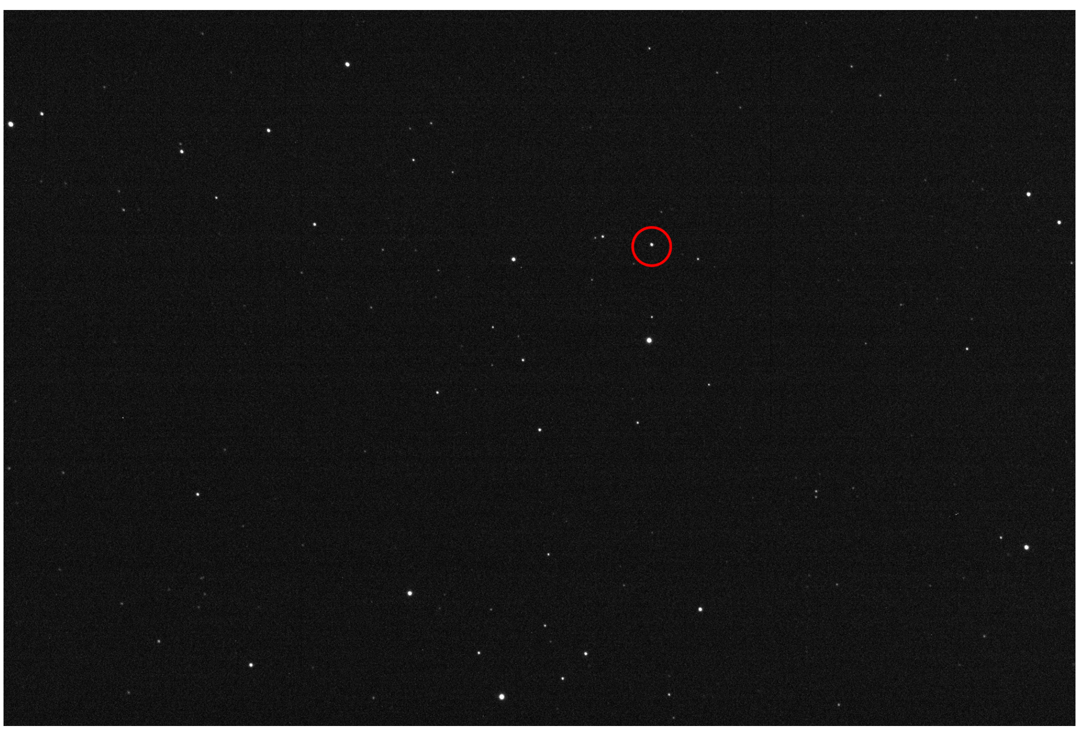
[Figure 2] Green filter, Data Set 1, BANZAI processed. Labeled with the star system we measured, this is a solo image, not combined with other photos at the same time. The only edits done in addition to the BANZAI processing involve adjusting contrast and brightness to more easily make out the stars.



54.0075	67.6845	-22.3703	31.2973	46.3565	56.2852	84.3869	66.1936	74.6879	30.2795	64.3811	70.1647	43.0775	59.8518	89.4947	71.9500	65.7167
64.2365	61.9442	32.7397	44.7763	94.5958	53.7132	77.6819	80.9343	36.0551	44.4520	52.2580	75.3419	57.6645	51.7859	66.7790	77.7211	65.7875
16.5298	100.074	112.214	44.0877	39.5367	45.7194	47.5189	79.1868	101.015	74.4295	100.293	91.3752	75.1998	86.8261	75.3096	51.4273	60.2295
60.3443	56.4262	103.684	47.2339	52.8543	69.1868	96.2242	151.036	131.464	134.970	131.315	91.9781	63.8201	86.5870	53.9319	83.8907	95.9244
87.0312	88.1469	86.0791	59.4319	49.5970	114.296	146.728	148.222	126.688	118.923	94.1016	113.296	120.186	101.635	110.989	57.7046	89.4748
102.413	80.8069	100.710	86.9200	100.141	96.6504	142.213	200.234	212.828	173.703	154.496	154.135	134.582	123.076	93.7344	51.8216	83.2082
74.8917	41.9426	108.097	106.281	160.036	137.736	194.378	266.944	286.938	200.882	217.077	172.151	169.221	135.113	90.9863	74.2006	121.484
44.0248	76.6678	87.2240	125.272	180.381	184.218	228.633	324.088	399.758	405.518	304.955	234.962	197.243	162.602	125.753	118.467	69.2365
83.1742	107.160	134.221	176.526	230.725	282.885	433.936	641.257	796.247	756.412	511.894	388.116	294.580	219.621	160.375	140.338	76.8526
57.6124	84.0506	135.838	208.703	279.253	483.162	926.902	1455.58	1742.28	1352.08	832.112	499.852	319.361	238.362	147.504	116.576	90.1485
120.877	84.4622	133.961	238.246	447.236	941.966	2143.14	3542.93	3820.52	2859.32	1500.28	736.178	421.303	272.587	167.022	101.434	68.7085
100.609	111.782	167.412	286.927	670.699	1559.79	3842.98	6358.03	6483.15	4309.97	2101.87	952.027	503.664	302.904	191.210	131.293	135.979
96.2060	136.280	129.135	349.121	765.867	1976.59	4612.19	7318.77	7359.37	4635.21	2159.17	1012.82	509.405	272.961	214.848	114.795	99.1068
84.8880	70.4710	178.808	381.685	712.348	1671.20	3611.27	5261.35	5244.53	3345.19	1728.15	854.149	515.874	253.779	148.766	124.340	111.428
61.6345	110.598	164.181	266.378	547.776	1114.31	2108.56	2627.49	2740.38	1912.83	1124.01	665.454	386.429	168.955	118.442	89.3212	77.2657
85.1085	120.552	158.483	259.329	396.926	733.274	1052.63	1287.34	1484.24	1105.59	724.576	470.606	287.180	183.797	135.982	98.0356	80.8195
52.6183	101.809	121.830	191.924	270.392	430.895	542.594	666.520	640.665	523.252	393.909	322.710	207.662	208.931	177.651	124.109	109.756
64.7435	79.2017	98.3283	129.248	185.725	215.096	278.247	344.112	334.802	304.318	241.563	168.694	168.614	157.841	115.306	107.402	99.9041
63.7788	110.134	108.555	117.221	110.419	132.029	183.773	161.829	187.982	181.343	163.883	149.881	175.015	130.836	121.547	43.9880	72.3231
25.0656	71.8460	74.7600	57.2611	89.5596	113.676	110.756	125.331	194.901	113.158	111.159	146.871	103.260	68.4557	97.5095	66.0310	10.5815
62.5729	91.8992	92.7793	83.0723	113.109	82.9423	78.2252	85.7535	87.7039	101.168	105.462	43.5231	76.2035	50.4229	98.7981	81.6105	50.3248
45.9705	78.4456	65.6618	42.7224	24.6248	108.634	77.1605	73.0943	51.3612	34.0828	75.8571	21.8166	68.4185	40.5026	21.7722	46.3972	56.3765
93.0960	132.979	65.5579	23.0019	95.1899	54.6089	61.1746	74.1970	72.6423	92.4759	65.0614	53.1753	35.0719	51.9978	38.9809	68.0017	63.9677
37.9064	75.3759	61.9922	72.6091	80.0793	84.0706	67.4655	66.9466	70.1720	85.3751	62.2582	28.0451	74.7264	53.4054	38.9432	73.8211	73.3516

[Figure 3] A closeup of the pixel values for a given shot of our star system from Data Set 1 with green filter. This is a photo of the pixels after combining the four photos into one. As expected, the numbers in the center are the maximum and the values surrounding it fall off with radius. Averaging these numbers was our first option to calculate magnitudes. We realized that this would lead to multiple uncertainties that could be avoided in just allowing AstroArt to calculate our magnitudes.

[Figure 4] This is an image of one of the less visible photos from Data Set 2. In some cases, these were too faint for Astroart to register, but after combining the two photos together, it was able to detect it.



[Figure 5] Red filter, Data Set 1, BANZAI processed. Images are sharp, and the contrast is more than acceptable.

[Figure 6] Blue filter, Data Set 1, BANZAI processed. Images are faint, and contrast is not as strong as green or red filters.

Data Analysis

Our data proved to be much more accurate with Data Set 1 as compared to Data Set 2. Focusing first on Data Set 1, our data of time to magnitude is displayed in Figure 7. This table also outlines an uncertainty calculated using the signal to noise ratio mentioned earlier. This uncertainty uses the following variables taken from the headers of our .fits files and other information from the LCO website [9].

N_R : $14.5\ (e^-)$

N_T : 337.3

τ : $12\ (s)$

F : $0.01\ (photon/(s \cdot cm))$

A : $5026\ (cm^2)$

$\Omega:\ 0.571\ (arcsec)$

$i_{DC}:\ 0.03\ (e^{-}/s)$

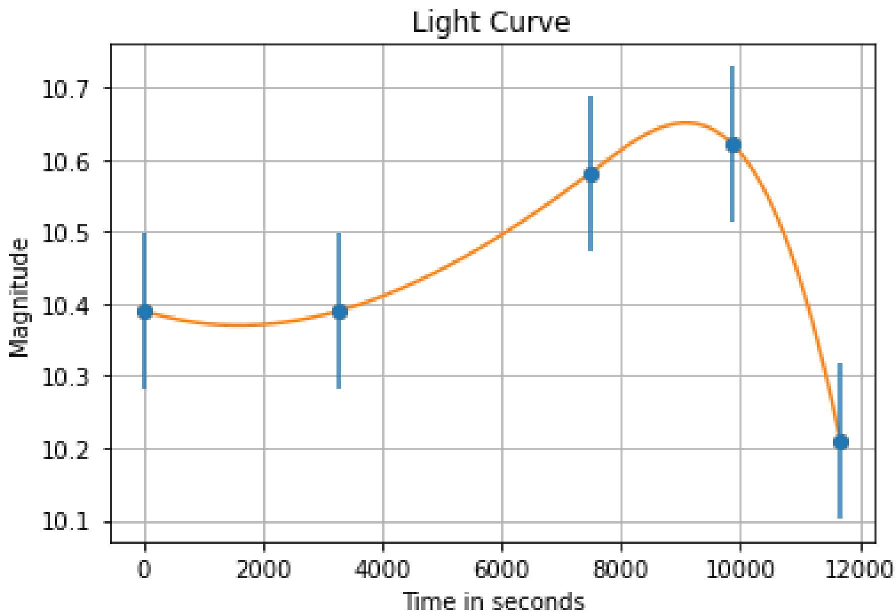
$$\frac{S}{N} = \frac{(0.01)\,(5026)\,(12)}{[(14.5)^{2} + (12)(337.3)]^{1/2}} = 9.24$$

$$Uncertainty = \frac{1}{\left(\frac{N}{S}\right)} = \frac{1}{9.24} = 0.108$$

Time average over four photos (hour:minute:seconds.millisecond)	Time (s), with the first point at 0 seconds	Uncertainty in time (s)	Apparent Magnitude	Uncertainty in Magnitude
02:11:36.629	0	0.001	10.39	0.108
03:06:19.115	3282.485	0.001	10.39	0.108
04:56:11.7575	9875.1265	0.001	10.62	0.108
04:16:5.7265	7469.0945	0.001	10.58	0.108
05:26:12.006	11675.373	0.001	10.21	0.108

[Figure 7] Table of time to magnitudes, along with uncertainties of both. The units for time do not really matter, as our analysis deals with differences in time across data points.

Ultimately, we obtained a light curve shown in Figure 8. This was a result of plotting the points of magnitude and time, and setting a cubic curve to it.



[Figure 8] Light curve plotting magnitude to time for Data Set 1. The error bars are a significant percentage of the graph.

From Figure 8, we can see there is a clear peak in magnitude, which is what we were looking for, yet it dips below its original base value after the peak. When taking into account the extent of the uncertainty, this graph makes more sense. If we were to disregard this last data point, we can treat the peak shown as the eclipse of the binary star system. Treating the distance from the first minimum to the maximum of the peak as half of the period, the period of the front orbit can be obtained. The first minimum takes place at t = 1600 seconds, and the maximum at t = 9500 seconds. The time difference between these two values is:

$$\Delta t = 9500 - 1600 = 7900\ seconds$$

This accounts for part half of the front eclipse period, which means that the full period of the front eclipse can be found with:

$$t = 7900 \times 2 = 15800\ seconds = 4.38\ hours$$

This period of 4.38 hours only shows us the time it takes for the star to eclipse around one part of the bigger star- in other words, these 4.38 hours only represent one part of the full orbit of the system. Therefore, we can obtain a more complete period of orbit of the star system by multiplying it by some constant:

$$T = 4.38 hours \times 2 = 8.76\ hours$$

or

$$T = 4.38 hours \times 3 = 13.14\ hours$$

We can say, hypothetically, that the orbit is somewhere between these two values. To average them out, we would get a potential period of orbit of 10.95 hours.

This is a rough way to calculate the orbit, but by comparing it to the accepted value of the orbital period, we can derive some other relationships. The accepted orbit period for the star system we chose (KIC 3833859) has an accepted period of 0.4317433 days, or 10.36 hours [7]. This means that the portion we calculated is anywhere from ⅓ to ½ of the full orbit. Specifically, we can show that our calculated eclipse is 0.4228 of the full orbit. If we assume the eclipse is circular, this means that the total orbital period would be the time it takes to go a distance of $2\pi r$, where r is the radius towards the center of mass. It can be seen through this fraction of the full orbit, that a light curve that shows the minima and maxima of an eclipsing binary star is not exactly half, as it would be if you were observing a flat circle. Since we know that the star can be approximated as round, we can do some analysis in figuring out an approximation of the radius of the center of mass. See Figure 11. The arc length that is visible to us is only .43 of the full circumference. By plugging this in to the formula:

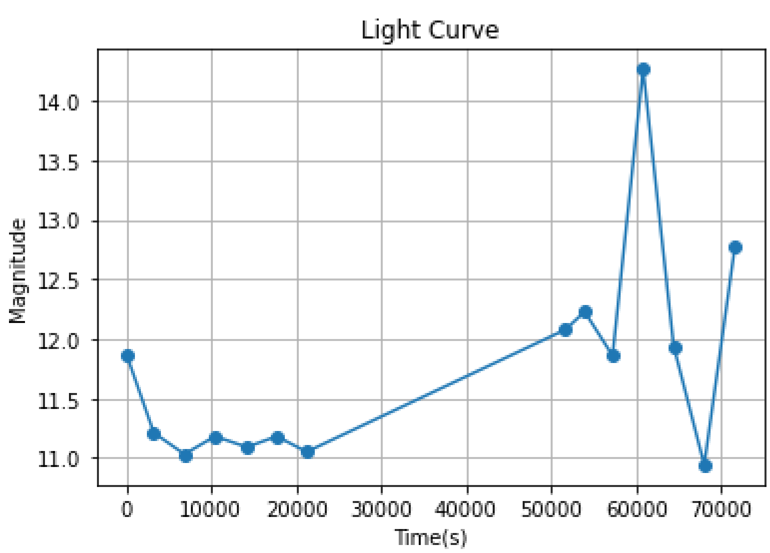
$$L = 2\pi r(\frac{\theta}{360}) = (0.43)(2\pi r) = 2\pi r(\frac{\theta}{360})$$

$$(0.43) = (\frac{\theta}{360})$$

$$\theta = 154.8^{\circ}$$

Our additional set of data extending over 24 hours had a much less accurate light curve. As can be seen in Figure 9, the data is very much staggered, and a smooth curve does not actually reveal as much as the points themselves.

a.



b.

Time in seconds	Magnitude
0	11.87
3216.675	11.21
6817.0665	11.03
10414.385	11.18
14176.2705	11.09
17682.824	11.18
21217.1975	11.05
51692.998	12.08
53934.7465	12.23
57223.7255	11.86
60818.1215	14.27
64415.599	11.94
68016.8655	10.94
71616.8255	12.77

[Figure 9]
a. Light curve plotting magnitude to time for Data Set 2. The error bars are a significant percentage of the graph.
b. Data used to create graph

Unfortunately, these results are mostly inconclusive for multiple reasons. Over the 24 hours, our data was predicted to include 2 whole orbits. With our data points so spread out and with so few over a long time, we miss valuable fluctuations between sets. In addition to this, at least one data point appears to be a little too high in magnitude compared to what we would expect. The earlier half of the graph does reveal some fluctuations whose timeline is somewhat on the scale of 8 hours that may be representative of eclipses.

Error Analysis

The accepted orbit period for the star system we chose (KIC 3833859) has an accepted period of 0.4317433 days, or 10.36 hours [7]. While we were not able to actually calculate an orbit period from our data, we were able to form assumptions based on what we did have. By multiplying our transient event period by 2 and 3, we got two values which can average out to give us a potential orbit period for the purpose of performing error analysis. This hypothetical orbit period would average out to give 10.95 hours. The percentage error from this would be:

$$Percent\ Error\ =\ |\frac{Actual - Expected}{Expected}|\ \times\ 100\ =\ |\frac{10.95 - 10.36}{10.36}|\ \times\ 100\ =\ 5.69\%\ error$$

Of course, this error comes from an assumption that the period of the full orbit would be 2.5 times the transient eclipse. This is not a valid assumption, as it is baseless. There are many factors that would go into determining what portion of the transient event makes up the full orbit. For example, the angle between the viewer and the direction of motion of the star would contribute to what percentage the transient event constitutes of the whole period.

While we did not get a full orbit of the binary star system, we did obtain a light curve for both Data Set 1 and Data Set 2. Focusing on Data Set 2, a lot of data became skewed. There were some magnitudes that seemed to be outliers. These could be outcomes of their processing on Astroart. Specifically, we found the magnitude of each star by aligning our photos up to the GAIA database, and gathering reference stars which affected the outcome of the magnitude. This could have been done incorrectly in multiple ways, such as not always selecting the same reference stars, not aligning the photos correctly, etc. There may have also been errors in getting the timestamps for each set of data. I used the SAOImage DS9 processor to get timestamps from the beginning and end of each data point. By averaging these times, we may have lost some important data. I converted them from Hours:Minutes:Seconds to just seconds, or just hours, which may have affected significant figures and the likes. However, it should be noted that these times and their errors are very insignificant in the broader picture of this specific data acquisition. They were on the scale of milliseconds, while we were looking at data in the range of hours.

One reason that our 24 hour data got so messed up may be attributed to having some of it take place during the day. This made the contrast much lower, and in some cases, Astroart had a hard time aligning the images with its database and each other.

IV Discussion

While we did not end up with a full orbital period, we did end up with two light curves which showed us a lot, not only about our star system, but also about data acquisition. At first, we thought that a longer period in which data was acquired would be better for this project, but that ended up not being true. As can be seen in our data, with an orbital period around 10 hours, the data points need to be close enough together to be able to see the dips and peaks of the curve.

If we were to do this project again, I would want to have a size of the system, so I could calculate the full period. I would also want to collect data over a longer period of time. We were limited by our time, but the Las Cumbres Observatory did have instruments which could have fulfilled a project like getting the whole orbital period. I would want to do another short orbit star system like this one, on the order of a couple hours, but I would want to record multiple sets of data over a year so I could get multiple light curves. I think it would be really interesting to see how the light curve of one system alters over the course of a year, as it would reveal so much more about the orbit.

I also would like to get multiple images within seconds of each other to get a complete curve with data for each moment. This way, I would not have to make curves which estimated lines, but I would have a full set. Ideally, I could have gotten a lot more insight into the eclipse if I had both the first and second eclipse of the system.

By getting multiple magnitudes over the course of three hours, we were able to put together a very telling light curve. The peak in the light curve proves the existence that binary star systems exist, a concept which was not originally accepted by most. The concept of being able to use apparent magnitude alone to create this graph and prove this phenomenon opens the door for so many scientific discoveries without super fancy technology. Utilizing processes like this allow things like the Hertzsprung-Russell Diagrams to be created, which are relied on for multiple different processes in astrophysics. While obtaining data towards this light curve, not only could we take a step towards piecing together the orbit of a binary star system, but also the existence of a binary star systems in general is proven in a simple, observable way.

V References

[1] “Eclipsing Binary Variables.” Sensing the Dynamic Universe: Eclipsing Binaries, lweb.cfa.harvard.edu/sdu/eclipsingbinaries.html#:~:text=Eclipsing%20binary%20variables%20are%20binary,light%20from%20the%20other%20star. Accessed 13 June 2023.

[2] “Introduction to Binary Stars.” Introduction to Binary Stars, 21 Apr. 2023, www.atnf.csiro.au/outreach/education/senior/astrophysics/binary_intro.html#:~:text=Perhaps%20up%20to%2085%25%20of,other%20and%20can%20exchange%20material.

[3] “Types of Binary Stars.” Types of Binary Stars, 21 Apr. 2023, www.atnf.csiro.au/outreach/education/senior/astrophysics/binary_types.html.

[4] A Short History and Other Stories of Binary Stars, core.ac.uk/download/pdf/153562167.pdf. Accessed 14 June 2023.

[5] Modern Astronomy, Prof. Gayley: Week #12, astro.physics.uiowa.edu/~kgg/teaching/modern/week10.html#:~:text=%2D%2D%20visual%20binaries%20are%20very,of%20gravity%20has%20to%20be. Accessed 13 June 2023.

[6] “Filters.” *Las Cumbres Observatory*, lco.global/observatory/instruments/filters/. Accessed 13 June 2023.

[7] “Kepler Eclipsing Binary Catalog - Third Revision.” Kepler Eclipsing Binaries, keplerebs.villanova.edu/. Accessed 13 June 2023.

[8] “Visibility Tool.” | Las Cumbres Observatory, lco.global/observatory/tools/visibility/. Accessed 13 June 2023.

[9] “About LCO.” Las Cumbres Observatory, lco.global/about/. Accessed 14 June 2023.

[10] “Data Pipeline.” Las Cumbres Observatory, lco.global/documentation/data/BANZAIpipeline/. Accessed 14 June 2023.