Determining the Properties of an Eclipsing Binary Star System

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This capstone project involves the analysis of an eclipsing binary star. This system includes two stars, where one will pass in front of the other from our line of sight on earth as they orbit around each other. This geometry allows for a simple analysis of the star system, in which a light curve can be obtained and used to determine certain properties about it. For the first portion of the project, numerous nights were spent at the RIT observatory to take images of the binary star system V445 Cassiopeiae. The images taken were cleaned and measured to produce light curves from the B and V band filters. The next steps of this project utilized these light curves to determine certain properties about the stars in the star system, such as their masses, temperatures, absolute magnitude, and the period.

Introduction

Many binary star systems have been analysed using the same method used for this project. This system works nicely when acquiring data because when one star passes in front of the other, it eclipses from our line of sight and there will be a dip in the brightness, similar to what we see during a solar eclipse. The dip in brightness will look similar to the image shown in Figure 1:

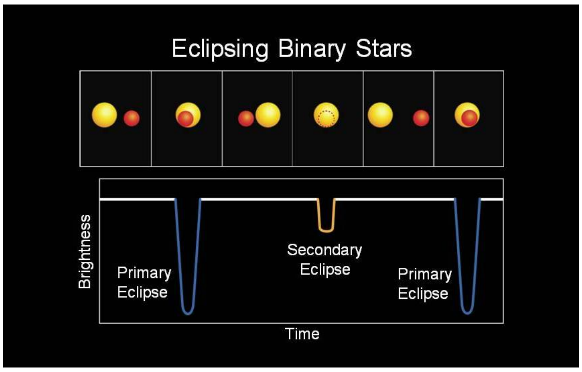

FIG. 1: Example showing how a light curve is made from a binary system.

Rather than simply picking a random binary system to analyze, there was quite a few criteria that the system needed to satisfy in order for this project to be successful in the time frame given to complete. Such criteria included the period, magnitude, and location of the binary system. Simbad and VizieR are two databases that have information on numerous star systems. The amount of information on each star varies, depending on how much research has been done prior. Using these databases, the star search was refined to only stars whose periods were short, stars were bright enough to measure accurately, and a location in the sky that would work for us and the telescope.

There was a few stars remaining in the catalog that satisfied these criteria, so the binary star system V445 Cassiopeiae was selected. For a few hours over select nights, the observatory was used to gather images of this binary system. The images taken from these nights were analyzed to determine if any were altered from certain conditions that may have changed during the observation time. Finding clear nights to observe proved to be a challenge, but eventually a process was created to find good nights to go out.

Determining Times to Observe

In Rochester, V445 Cas stays in the sky for the entirety of the night. The software Stellarium is able to see exactly when the sun rises and sets, so different days throughout the semester were selected and starting times of observations could be determined.

Date (2021)	Time
September 1st	8:30pm-5:00am
September 15th	8:15pm-6:00am
October 1st	8:00pm-6:30am
October 15th	7:30pm-6:15am
November 1st	7:15pm-6:00am

This information became advantageous when it came to getting the last portions of data needed to complete the light curve. This posed a bit of a problem later in the semester as the weather became less ideal. Once this step was completed, it was time to become familiar with the observatory equipment.

First Observatory visit

The first observatory visit took place on September 9th with my capstone peers and mentor. A procedure was produced during this time and proceeded as follows:

1. Place cameras on telescope and turn equipment on
2. Take dark and dome-flat images

3. Locate star and set up tracking system
4. Rotate dome
5. Set up system to flip between V band and B band filters for each image
6. Set the exposure to 30 seconds and set the number of pictures to a large number

The cameras that were placed on the telescope served different purposes. The small camera was attached to the side of the telescope and acted as a tracking device. The larger camera was attached at the bottom of the telescope and was responsible to taking the images.

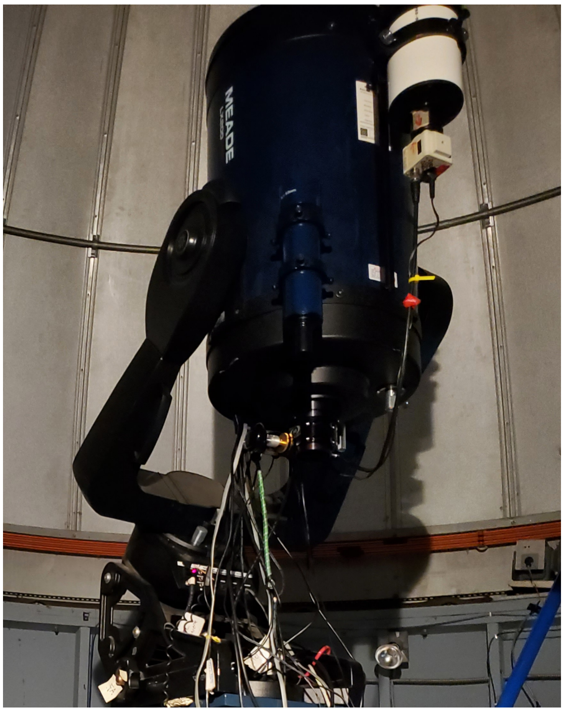

FIG. 2: Date: 09/08/21 8:25 pm, Picture from inside of the observatory showing the setup of the telescope. The white camera is the small camera and the large camera has yet to been inserted into the bottom of the telescope.

The next step after setting the cameras up was to take dark and dome-flat images. A dark image is taken by placing the telescope lens cover over the telescope and taking an image. Dark images were taken with the V and B band filters at 2 and 10 second exposure times respectively, which would then be matched with the target images later on to clean them.

The image should be entirely dark, but that is not the case. That's because there is thermal noise from within the telescope. These frames are important for the image reduction process because that thermal noise is still present when taking pictures of the target. Now, dome-flat images are used for a similar purpose, but capture a different aspect that must be accounted for. To take these images, the telescope was aimed at a white piece

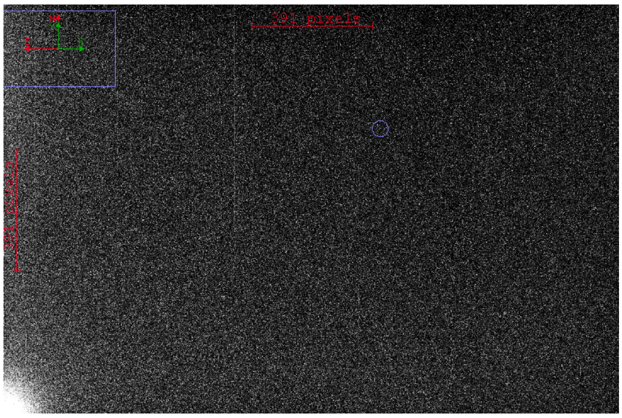

FIG. 3: Date: 10/19/21 9:20 pm, Image showing the dark frame using the V-band with a 2 second exposure time.

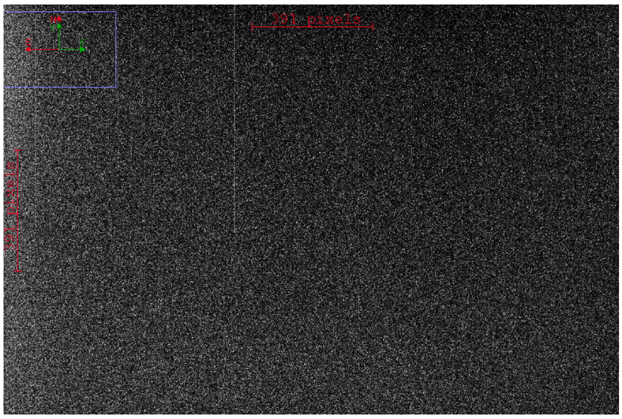

FIG. 4: Date: 10/19/21 9:25 pm, Image showing the dark frame using the B-band with a 10 second exposure time.

of cardboard and the dome was rotated so there was no shadow on the cardboard. The same exposure times were used for the same bands with these images.

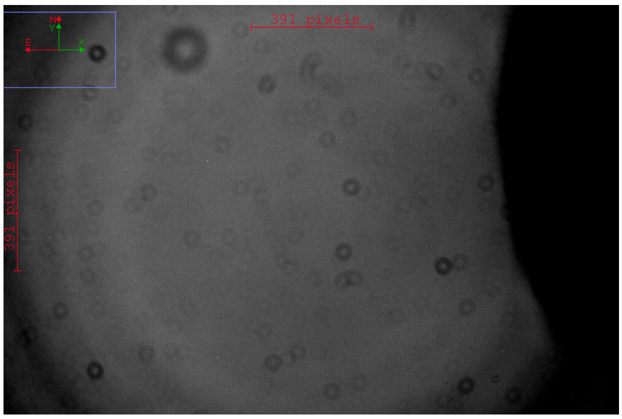

FIG. 5: Date: 10/19/21 9:35 pm, V-band image showing the light irregularities and dust particles that naturally exist

Once again, this is something that must be accounted

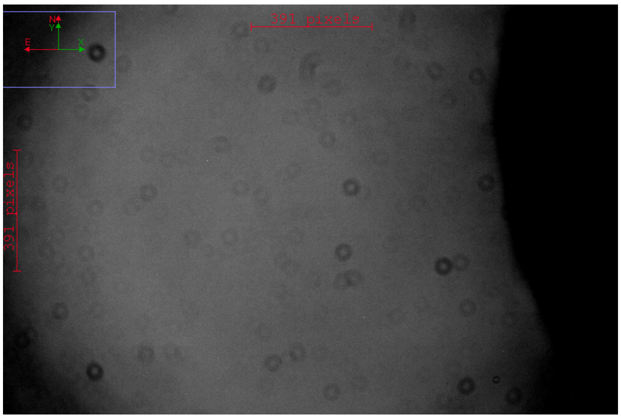

FIG. 6: Date: 10/19/21 9:40 pm, B-band image showing the light irregularities and dust particles that naturally exist

for when cleaning the images later on. The small differences in each band play an important role as well. The odd shadow present on the right hand side of the dome-flat images comes from light falling on a pick-off mirror, hence creating a rather large irregularity. Luckily, this does not pose a problem, at least for the target star, as the target star should remain in the middle of the screen when taking pictures. Then using the MEADE telescope's simple target finding function and guided assistance, the telescope was ready to take images.

The target star was located using a finding chart created through the software Aladin. The star system was centered in the middle of the frame by locating the reference stars and adjusting the telescope accordingly. Finally, using MaxIm DLe to communicate to the telescope, a process was setup to take images that flipped between the V and B bands with a 30 second exposure time and the first observation session was ready to get underway.

First Observation Session

FIG. 7: Date: 09/18/21 8:24 pm, V-band image of sky with target star

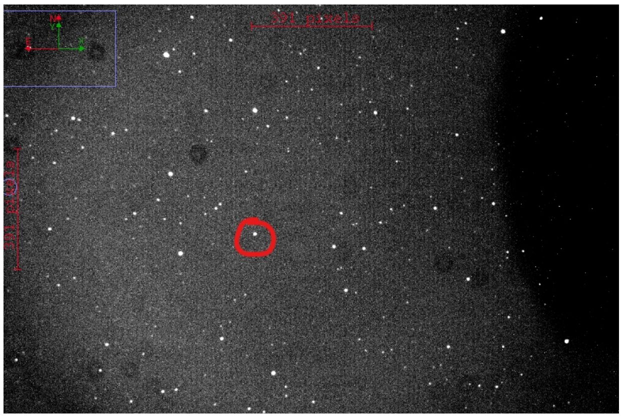

FIG. 8: Date: 09/18/21 8:25 pm, B-band image of sky with target star

The first observation session took place on September 18th, 2021 between the times 8 pm and 12 am. During this period, every 20 minutes the telescope had to be checked on to see if it was still oriented correctly and that it was still between the edges of the dome slit. Occasionally, rotating the dome slit was necessary to accommodate for the telescopes guided motion.

One of the biggest steps in determining what portions of the light curve still needed to be filled was to determine the phase coverage on the nights of observation. The phase refers to what moment in the binary systems orbit the stars are in. This value falls between the values 0 and 1. Astronomical times are measured in Julian Dates, which then must be converted into the phase. Luckily, there is a rather simple equation used to convert these times:

$$\text{Phase} = \frac{(\text{JD} - \text{Epoch})}{\text{Period}} \tag{1}$$

The Julian Date depends on the time and day that the observations took place. The Epoch refers to a reference point in time that is used a constant. In this case, that value is equal to 2456886.3860. The period = 0.6735225000 days, which is about 16 hours.

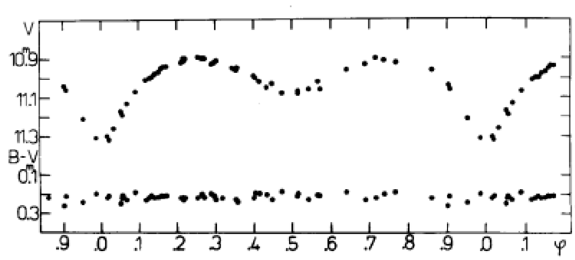

FIG. 9: Light curve taken from article discussing their observations of V445 Cas

For following nights that were supposed to be clear, calculating the phase beforehand could aid in picking a specific night so time wouldn't be wasted collecting images that would produce the same portions of the light curve. For the images taken during the first observation session, the phase gathered fell between 0.68-0.99.

Image Reduction Process

There is a lot of light noise and dust particles present in the initial images gathered, so a process using the dark and dome-flat frames must be carried out to eliminate these defects in the images. The process goes as follows:

1. Make master dark frames (2, 10, 30 sec)
2. Subtract dark frames from dome-flat frames
3. Make master flat frames
4. Subtract appropriate dark frames from target images
5. Divide target frames by master flat frames

This process was tedious, but with the help of the software AstroImageJ, it could be done in a simple fashion. Dark images were taken in sets of 20, so creating master dark frames involved combining all the images into one median frame. Three master dark frames were created, one with the 2 second exposure time images (for V-band dome-flats), one with the 10 second exposure time images (for B-band dome-flats), and one with the 30 second exposure time images (for the target images). Before directly dividing the dome-flats out of the target images, it is necessary to first subtract the thermal noise out of the dome-flat frames.

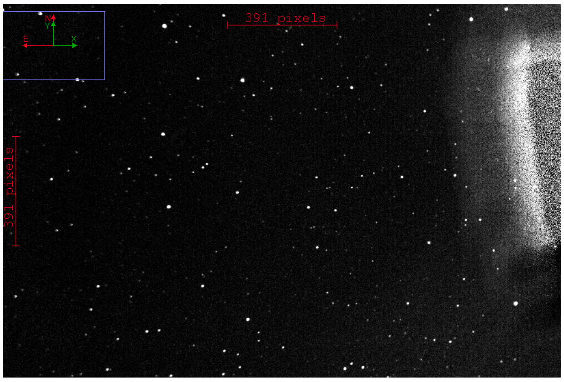

FIG. 10: Date: 10/19/21, Clean image after the reduction process

Once that is complete, the images were compiled into two master dome-flat frames, one for the V-band and one for the B-band. Now having the appropriate dome-flat and dark frames, the target images could be reduced to produce clear, measurable images.

Data Analysis

Now that all of the image irregularities had been eliminated, the light curve could be produced using aperture photometry. Aperture Photometry is a process used to measure the amount of light in a given area. The given area, using AstroImageJ, is a circle placed around the target star and reference stars.

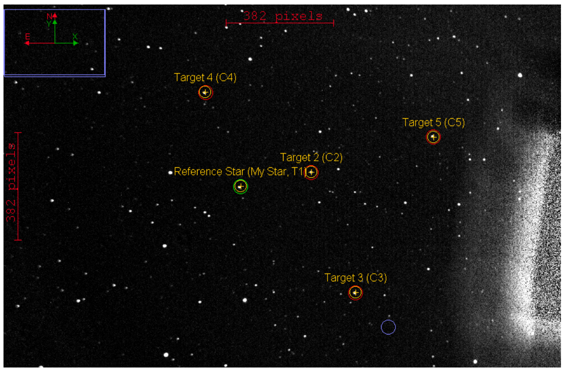

FIG. 11: Date: 11/02/21, Shows how aperture photometry works using AstroImageJ and what stars were used as a reference.

This process took the longest amount of time, as this process not only had to be applied to each individual image, but had to be done in segments. This resulted in numerous tables being created that had to be combined into one. The tables generated included information about the Julian Date of each image taken and the brightness of the stars at each time. These were the columns that were used to generate a light curve. After six observation sessions at the observatory, a complete light curve was able to be produced.

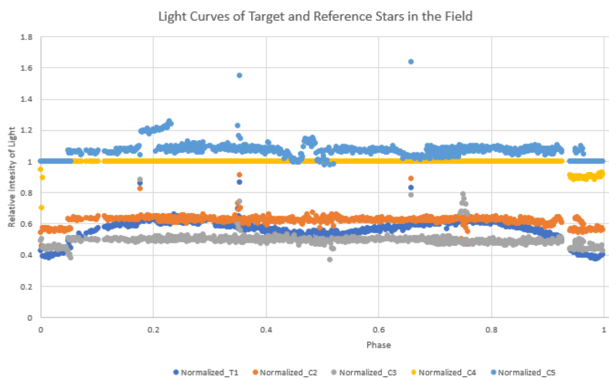

FIG. 12: Date: 11/27/21, The target star V445 Cas can be seen as the only line that isn't straight. It has been compared to other non-binary stars to show the curve.

The light curve was separated from the reference stars to clearly show the dips at the times of minima.

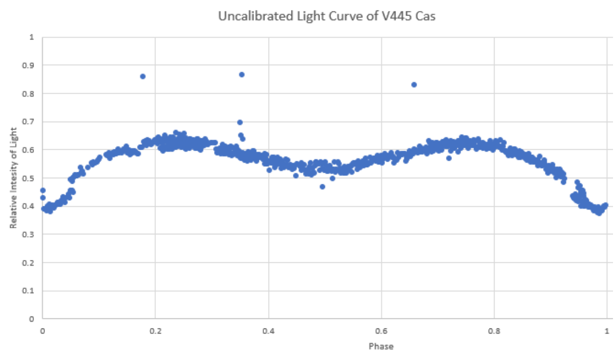

FIG. 13: Date: 11/27/21, Shows the light curve of V445 Cas by itself.

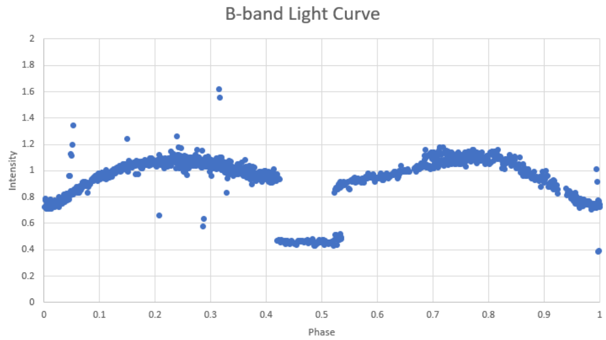

FIG. 14: Date: 11/27/21, Initial light curve created with the b-band images.

Problems Along the Way

This project didn't go without problems. A problem that had to be accounted for each night of observations was the clarity of the night. During certain periods of the night, there was a possibility of a cloud passing between the telescope and the star, creating a visibility problem. Another problem that existed on nights of observation was that the telescope would become too cold and ice crystals would start to form on the telescope, altering the images further. These images were simply not used during the aperture photometry process. Further problems occurred when scheduling times to observe the target star. Luckily, along with the assistance of my mentor, these problems could be worked around and eventually enough images were taken to produce a full light curve.

Plan for Capstone II

The light curve that was produced was only with the V-band images, so the first thing that needs to be completed was creating the light curve with the B-band images. Once that has been completed, calculating the properties about the binary star system could go underway, such as the mass, the period (which has already been determined from other sources, but we can re-verify), the absolute magnitude, and the temperature.

Creating B-band Light Curve and Cleaning Light Curves

Using the same process used to create the V-band light curve, the B-band light curve was able to be quickly produced. The initial curve had a glaring problem located right in the center, around the second dip. In order for future measurements to be accurately calculated, the light curves needed to be void of error. Sections that didn't look optimal in both graphs were re-examined to try an determine the source of the error. For the V-band, the primary dip was slightly offset. To correct this error, the normalization calculation was carried out against for that section and this fixed the problem. For the B-band, a deeper analysis needed to go underway, for the error was not easily identifiable. The problem can be seen to exist throughout all the reference stars as well.

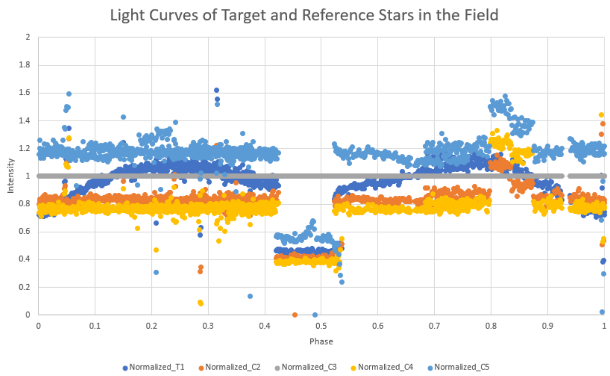

FIG. 15: Date: 11/27/21, B-band light curve against reference stars

This suggested that there may have been something wrong with the comparison star being used. After taking another look at the images in this section, it could be determined that the comparison star was too close to the saturation region on the right side of the cleaned images. After conducting the same normalization procedure with a different comparison star, the problem was fixed, and both of the light curves were optimal for further usage.

Determining the Correct Period

Although a period was given from the Simbad database, it could be possible that this value has changed over time. The period given is .6735225 days. By choosing different periods, the calculation for the phase will produce different values and alter the graph in different ways. Ultimately, if there was a different period for this system, it would produce a better looking light curve.

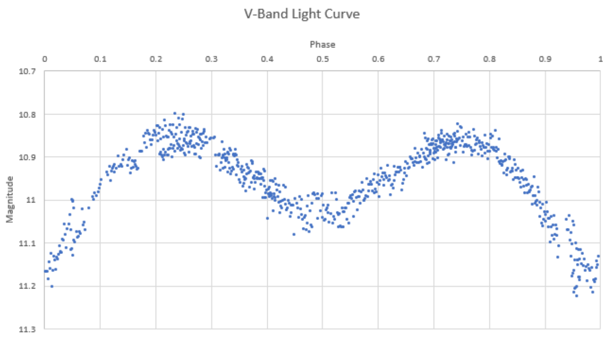

FIG. 16: Date: 11/27/21, V-band light curve after eliminating error

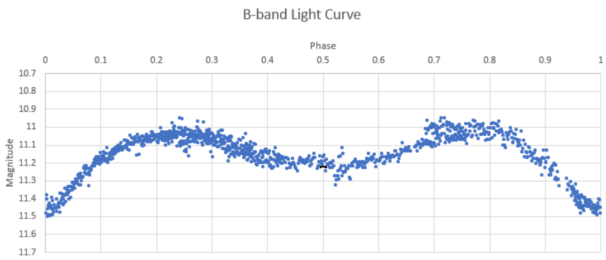

FIG. 17: Date: 11/27/21, B-band light curve after eliminating error

However, by slightly altering the period by increasing it and decreasing it by a small margin, the following light curves were produced.

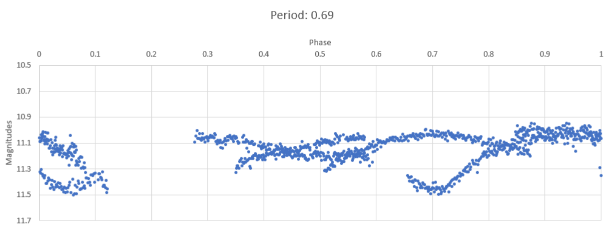

FIG. 18: Date: 11/27/21, Light curve with an increased period

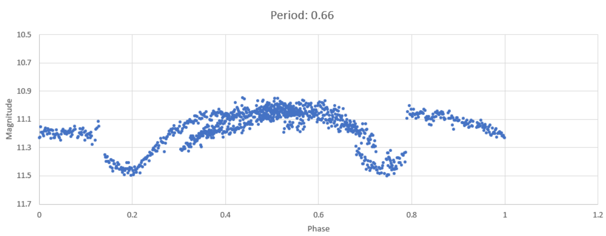

FIG. 19: Date: 11/27/21, Light curve with a decreased period

It could be quickly concluded that the original period given by Simbad was the correct period when carrying out the measurements for the phase. These graphs showed no pattern, with a lot of data overlapping and phase ranges where there was no data. Another method used to see if this period was the best fit was by plugging the data into NASA's Exoplanet Archive. The calculation carried out by this program is uncertain, but with the same data given, the same period was perceived to be the best fit.

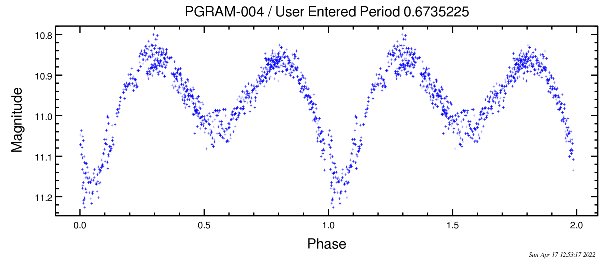

FIG. 20: Date: 11/27/21, NASA Exoplanet Archive graph produced using correct period

This period is the current period of the system. Another process could be utilized to determine if there was any change to the period over time. To do this, times of minima were gathered from numerous other astronomers that had measured this value during their observing times. These times of minima could be substituted into the phase equation to determine if the primary dip occurs where it would be expected (at 0 phase). Plotting these values created an O-C graph, which shows how the times of minima compare to one another. If there is an apparent trend in the data, then the period could be changing over time and the star system isn't in constant motion.

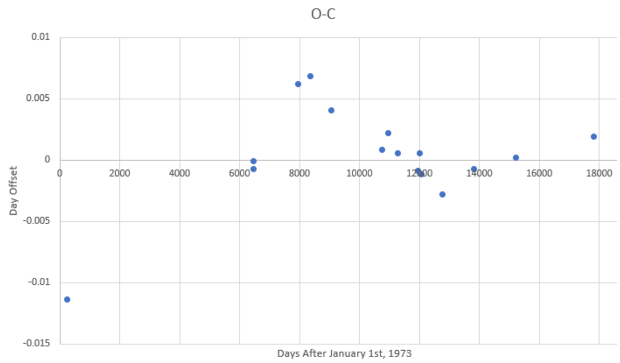

FIG. 21: Date: 11/27/21, O-C graph produced with times of minima measured from other sources

Every value gathered for the time of minima was plotted, including the measured time of minima from my V-band light curve (times of minima gathered from other sources only existed in the V-band). After a brief error analysis, it was easy to see that there was no trend in the data, but the offset from each of the points may be from noise in the data or human error.

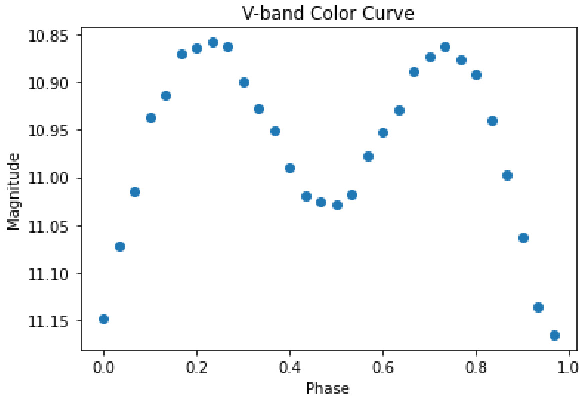

FIG. 22: Date: 11/27/21, Binned light curve with the V-band images

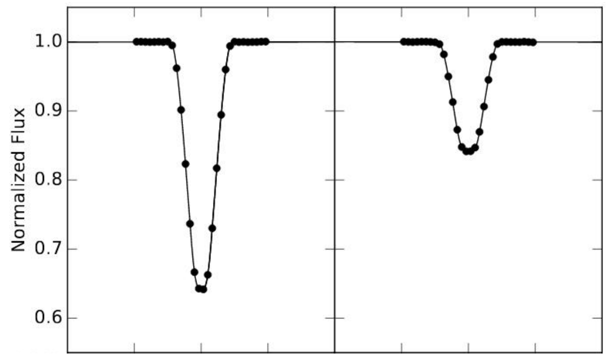

FIG. 25: Date: 11/27/21, Shows how the dips in the light curve can be used to determine the temperature ratio of the stars. Figure 3b taken from Fetherolf et al., AJ 158, 198 (2019)

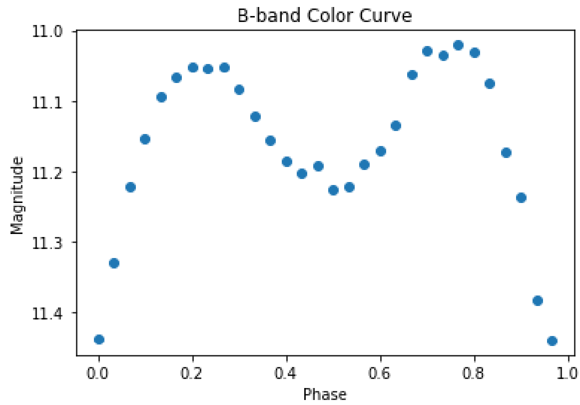

FIG. 23: Date: 11/27/21, Binned light curve with the B-band images

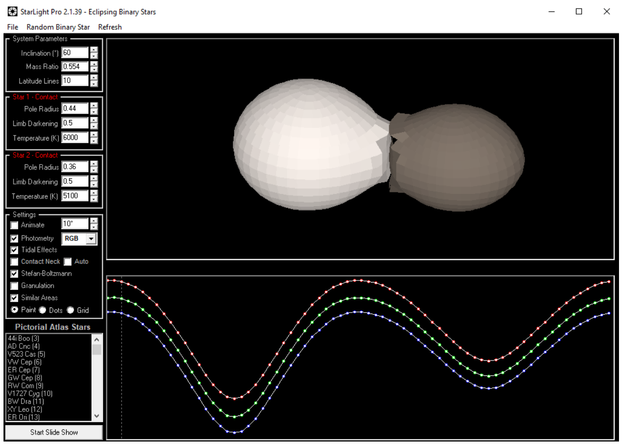

FIG. 26: Date: 11/27/21, Simulated system with values representing the star system

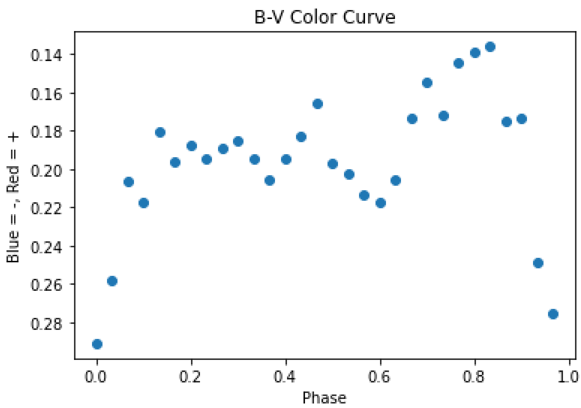

FIG. 24: Date: 11/27/21, Graph produced by subtracting the binned B-band light curve and the binned V-band light curve to show a change in temperature

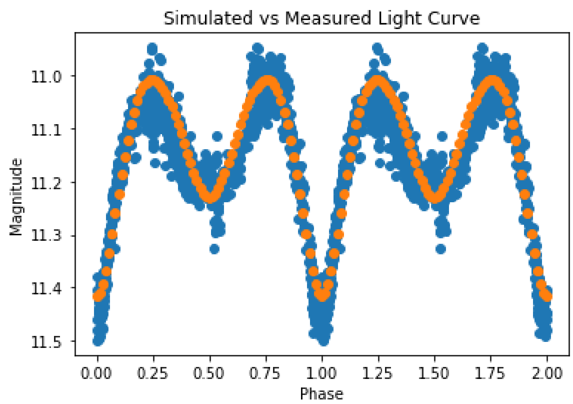

FIG. 27: Date: 11/27/21, Light curve taken from the simulated system used to compare to measured light curve.

Acknowledgments

I would like to thank Dr. Richmond for being my mentor for this project and providing insight on what I should be looking for. Also, thank you Dr. Pierce for overseeing the Capstone I projects along with RIT Physics Department for making this project possible. Thank you to my Capstone colleagues Remi and Nititee for sharing your ideas for this project as well. This research has made use of the Stellarium planetarium and the Simbad and VizieR databases and "Aladin sky atlas" developed at CDS, Strasbourg Observatory, France.

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[1] @ARTICLE1996IBVS.4381....1A, author = Agerer, F. and Kleikamp, W. and Moschner, W., title = "New Elements of V628 Cygni", journal = Information Bulletin on Variable Stars, year = 1996, month = oct, volume = 4381, pages = 1, adsurl = https://ui.adsabs.harvard.edu/abs/1996IBVS.4381....1A, adsnote = Provided by the SAO/NASA Astrophysics Data System

[2] @ARTICLE1974IBVS..867....1S, author = Szabados, L., title = "V445 Cas is an Eclipsing Variable", journal = Information Bulletin on Variable Stars, year = 1974, month = feb, volume = 867, pages = 1, adsurl = https://ui.adsabs.harvard.edu/abs/1974IBVS..867....1S, adsnote = Provided by the SAO/NASA Astrophysics Data System

[3] @ARTICLE1986MitVS..11...25H, author = Häußler, K., title = "Verbesserte Periode von V445 Cassiopeiae.", journal = Zentralinstitut fuer Astrophysik Sternwarte Sonneberg Mitteilungen ueber Veraenderliche Sterne, keywords = Beta Lyrae Stars:Periods, Delta Cephei Stars:Periods, Periods:Beta Lyrae Stars, Periods:Delta Cephei Stars, year = 1986, month = jan, volume = 11, pages = 25-26, adsurl = https://ui.adsabs.harvard.edu/abs/1986MitVS..11...25H, adsnote = Provided by the SAO/NASA Astrophysics Data System

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