Photometry Of The Cepheid Variable Star XX-Cygni

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Using image calibration and Photometry, the distance between Earth and the Cepheid variable star XX-Cygni will be found .With the aid of astronomical cameras and coding techniques,graphs and plots will be used to ultimately create a light curve that will give vital information about the star being researched. Error analysis using specific formulas and a discussion talking about ways to improve follow at the end of the report. The calculated distance in this experiment is 1424.3 Parsecs.

1 Introduction

Photometry is a scientific method used in Astrophysics to measure the brightness of objects in space. Brightness is more commonly referred to as astronomical magnitude or flux in this field of Physics. Using the University Of Exeter Observatory, photos will be captured of the Cepheid variable star 'XX-Cygni'.

The star was discovered in 1904 by Lydia Tseraskaya[5]. Lydia discovered 219 variable stars in her career at the Moscow observatory but publications of her findings were under her husbands name. Her husband was a Professor of Astronomy at Moscow University and was the director at the Observatory his wife worked at. This is why it states that XX-Cygni was discovered by 'W.Ceraski' instead. Located in the milky way galaxy, XX-Cygni is blue/white in colour and cannot be seen by the naked eye. The stars radius is 2.86 times bigger than our Sun and is located 1162.9 parsecs away from Earth[9]. With a temperature of 6982 Kelvin, this star is hotter than our Suns by 1205 Kelvin[6].

In the Milky Way galaxy, this star is located on the boundary of the Cygnus constellation. This constellation represents a swan like structure and Cygnus translated from Greek roughly means Swan[6]. The reason that this experiment focuses on this star particularly is because it has some interesting characteristics. XX-Cygni pulsates meaning it varies in luminosity. It also has a period of only 0.135 days[5] and its flux varies by over one astronomical magnitude within a couple of hours. This in turn allows a light curve of Magnitude vs time to be plotted easily.

The goal of this experiment is to determine the distance to XX-Cygni. This will be done by coding, using time-series Photometry and making quantitative measurements of the magnitudes of the star. Carrying out data processing of the images created by the Exeter observatory will lead to the production of a light curve that can be analysed to find the distance.

2 Theory

There are many processes involved with this experiment but Photometry is the most predominant. This technique works by measuring the flux of electromagnetic radiation from celestial objects. The Exeter observatory uses a CCD camera to take it's photos[4]. This stands for charge coupled device and is a light sensitive integrated circuit that captures images converting photons into electrons. A CCD sensor is then used to break the image elements up into pixels and then the pixel is converted into an electrical charge where the intensity can be related to the intensity of light captured[8].

Aperture photometry is easier to use in this experiment as there were a small number of sources in the photos taken. This works by defining a region of the image that includes the target and sum up all of the counts in that region. Subtracting the sky brightness by using another image with no stars and calculating the aperture can the reveal the the magnitudes of the target star.

The magnitude system is used importantly in astronomy to quantify the flux of an object. It's used in a logarithmic scale because according to history the response of the eye is logarithmic and because we are working with such large numbers[4]. Apparent magnitude of a star is given by [4]:

$$m - m_0 = -2.5 * log_{10}(\frac{F}{F_0}) \tag{1}$$

where m is the apparent magnitude of the star, m_0 is the magnitude of the standard star. F is the flux of the star and F_0 is then trivially the flux of the standard star. To calculate the intrinsic brightness of a star absolute magnitude is needed. In other words this means the magnitude of an object if it was located at a distance of 10 parsecs[4]. A parsec is defined as the distance where the mean radius of the earths orbit subtends an angle of one arc second. This equation is[4]:

$$m - M = 5 * log_{10}(\frac{D}{1PC}) - 5 \tag{2}$$

where absolute magnitude is M and the distance is D. Before moving onto how the methodology of this experiment works it is useful to know what telescope and camera was used in capturing these images. The Exeter observatory boasts a 14 inch Celestron EdgeHD Schmidt-Cassegrain. It is attached to an Astrophysics 1100 GTO mount and sits within a dome. It has a robotic focus and most importantly as discussed before the CCD camera. The camera is a SBIG STT-3200 and can capture up to a resolution of 2184×1510 6.8μm light sensitive pixels[4]. Python was used as the data analysing software and code was created to get to the desired value.

3 Method

This section will discuss the path taken to get to the desired outcome of this experiment. Using the theory talked about above photometry and the creation of a light curve can be used to understand the distance between Earth and our target star XX-Cygni.

3.1 Image Calibration and the Production of World Coordinates

The first step is to pick what night of observations will be processed. As multiple nights may make differences in results it is wise to look through the photos briefly before choosing. Using two or more nights will make the experiment overall more accurate and less subject to scientific disregard. This is due to proving the reproducibility of the overall aim of this task.

After downloading all the data needed, code can be written to assign the images taken on a specific night into a good and bad pile. Using bad photos can be detrimental to the outcome of this report so it is important to take this step very seriously. Writing code to do this can make this step more efficient by using automation. It will automatically convert the photos from a FITS format into a raw data file that can be viewed on the computer.[1]

Once this step has been completed, analysing image quality manually will ensure the data is as accurate as possible. Looking through the raw data images processed from the last step, deletion of photos with obscure elements in them will aid this experiment. This may include, stars in the image appearing twice, all stars appearing as long streaks or torus shaped stars. In addition, satellites passing the image, images without stars at all or that the stars look like they make sudden movements. A good image is one that can allow the viewer to distinguish between objects in the photo. No blur or obstructions make for good data.

A FITS file will contain image data and also a header which contains useful information about the image. Understanding whether the telescope software has automatically subtracted the dark current and bias images before processing them is the next step. Atmospheric effects such as scattering can be removed by finding the darkest pixels in an image and subtracting their values from all the remaining pixels in the photo. Dark frame subtraction is a way to reduce image noise when using long exposure times and bias frame subtraction is the process of deleting the first photo on the camera that night that tests the chip is working in a linearly basis.[1]

After this step, flat-fielding is used to process these images even further in the future. This is done in three steps. Firstly normalising each image by its median value. Then, combining each of the separate flat field images into one master image. Finally, normalising these images reduces the effect of varying brightness creating an image that looks more constant. No vignetting in any of the final results. Combining the images reduces statistical noise and makes the image look smoother. This image created can then be applied to the target images discussed above to produce captures of the night sky that are easier to understand.[1]

Dividing the target images by the master flat field image will create a set of images that are optimised for data analysis. The relative brightness in the stars should be closer to reality and the background appears to be almost constant with colour gradient.

Even though the header of the FITS image files give information about the orientation of the camera this shouldn't be used when obtaining sky co-ordinates. This is because the driving equipment is not precise enough to pinpoint targets to within one pixel. The way to overcome this is to use a resource called astrometry. It takes an input image of the night sky and attempts to create world coordinate parameters. It works by matching the sources detected in the image against an database of images. If successful it will turn image pixel coordinates into right ascension and declination coordinates.[1]

With this information, images from earlier can be displayed with an overlay of grid sky coordinates. Drawing a circle around stars is also useful in pinpointing certain stars in the image. Most importantly pinpointing XX-Cygni. At this stage of the experiment a set of images that are calibrated with celestial coordinates have been produced. With this, locating any star with known sky coordinate positions is very simple.

3.2 Photomotery

The next section of the method is useful as it allows us to identify our calibrated stars and XX-Cygni from the images calibrated previously. Using a file with data including the star name and coordinates, a python script can be written that takes these coordinates and creates a circle around each star in the image. Doing these for all of the star and adding a legend to the plot will allow the plot to be easier to read for readers and to make analysis easier in the future when trying to distinguish between stars. When performing Photometry a good patch of sky around the star is needed so when classifying the stars it is important to understand whether to include it or not. [2]

The next step is to define apertures on each of the chosen stars. Pip installing the module photutils onto a computer will be very beneficial as it performs photometry for astronomical images. Giving the coordinates of the sky will create an aperture definition. As discussed in the theory section using aperture photometry is easier for this experiment. Using a python script, a circular aperture can be created to extract the target flux and annular aperture sky flux. To perform photomotery the coordinates of the circular aperture just created need to be converted into Cartesian pixel coordinates. When creating the aperture circles for each of the calibrated images it is vital that the circles don't include other local stars. In this case change the size of the circle to make sure this error uncertainty is diminished in the final result.[2]

Photometry can now begin. Passing the apertures through the photutils will sum up all the counts. It will produce two lists. One for the apertures of the target and one for the sky annulus. Now we can just get the target aperture by subtracting the sky signal from the total area of apertures. Now we have a number that can be converted into flux. In theory the number of counts on the image is proportional to the number of photons received by the CCD. Using the exposure time, rate of counts per time can be calculated. This then is also proportional to the luminous flux. Then after this we need to convert from flux to instrumental apparent magnitude. Using equation one and iterating over all the data we can gain the values for each of the stars.[2]

If we want to continue using instrumental magnitudes, we need to do differential photomotery to put the magnitudes onto a standard scale. Plotting the difference between literature magnitudes and instrumental magnitudes can show how much they vary from star to star. This allows an insight to what could be creating uncertainties in the final data due to the offset of the calibration. Doing this over all of the stars in the data-set and then plotting a graph of the calibrated magnitude vs time shows a small section of the time series plot.

This should create a graph that has distinct horizontal lines with a dashed line to show the theoretical literature values. From this it is clear to see which one is XX-Cygni out of all of the calibration stars. The final step is to create a light curve of information from all of the data set. After this a graph of calibrated magnitudes will be produced with the light curve. It will be varying in magnitude due to the fact that XX-Cygni is a pulsating star.It experiences periodic expansion and contraction on the surface level of the star causing it to heat and cool. Finally after this, all of the data needed to find the distance between Earth and XX-Cygni has been gathered. The period of this star can also be calculated in the final readings of this experiment.[2]

4 Results

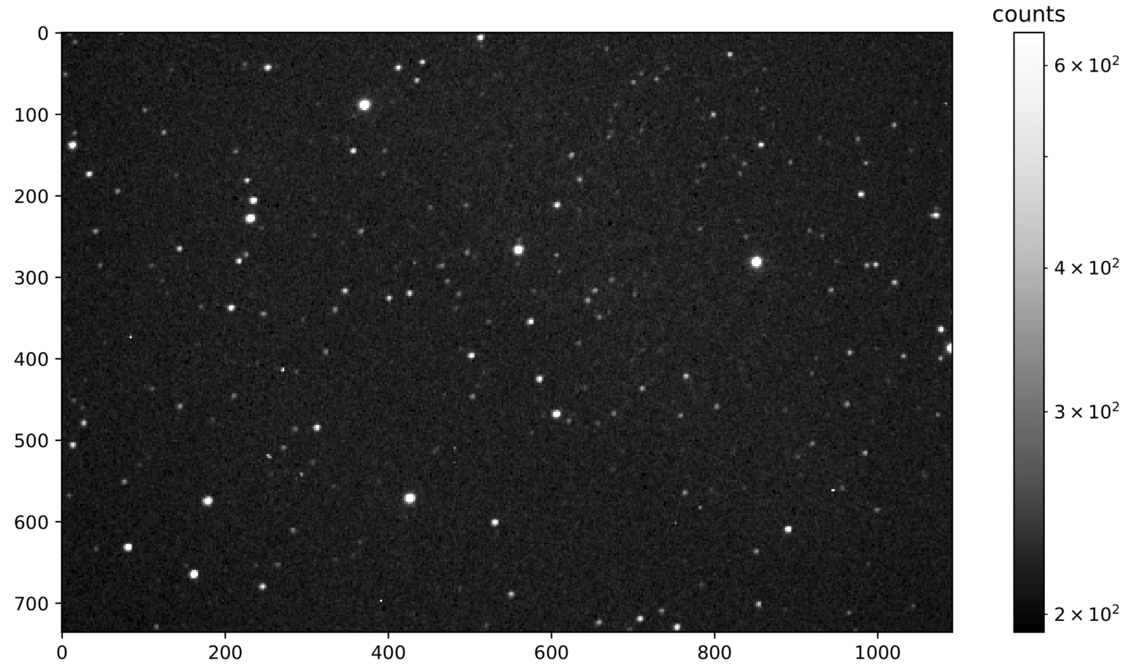
4.1 Image Calibration

In this section of the report the results from the experiment explained above will be presented. The investigation for XX-Cygni starts with picking the set of night observations. In this case, the 18th November 2016 was picked. This night was picked because after looking through the raw images it was clear that this one would give a good set of accurate results. This being of high importance in an experiment of this caliber.

So to start after picking the night sky that was going to be analysed, it is vital to remove the raw images that would hinder the final results. The photos removed either included an anomalous source captured, or in this case a satellite was in the way or the image wasn't to a high enough quality as some of the other photos had. There was a total of 16 raw images deleted. Number 87, 119, 125, 145, 146, 147, 149, 150, 187, 188, 192, 236, 237, 318, 330 and 346 were removed from the initial folder.

After this the production of an example image to check the coding process was created. This is vital in the experimental process because it can point out whether parts don't work before starting calculation. Ultimately, reducing unnecessary uncertainty. This example image is shown below:

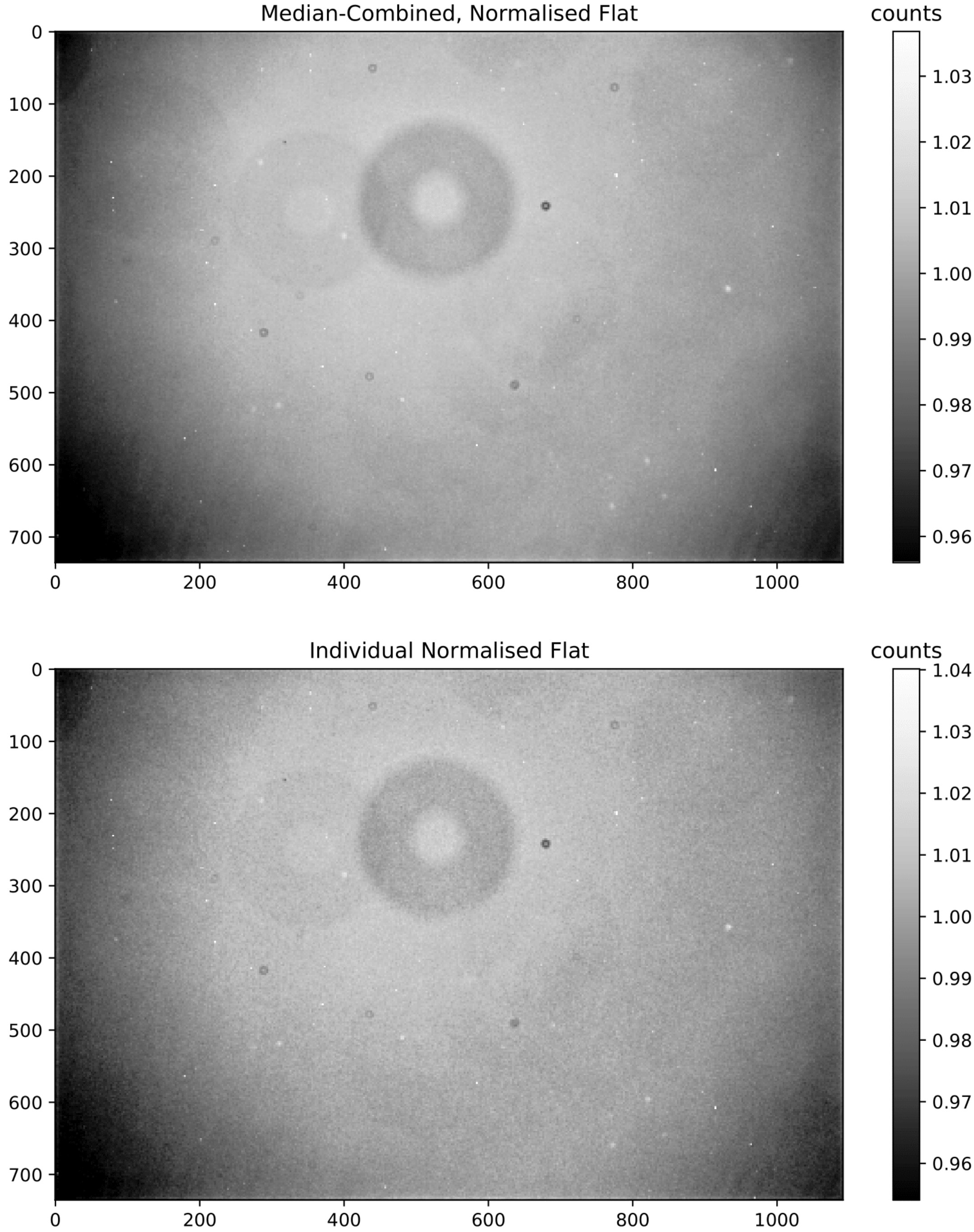
Figure 1: Test image for the reduction of unnecessary uncertainty



4.2 Flat fielding

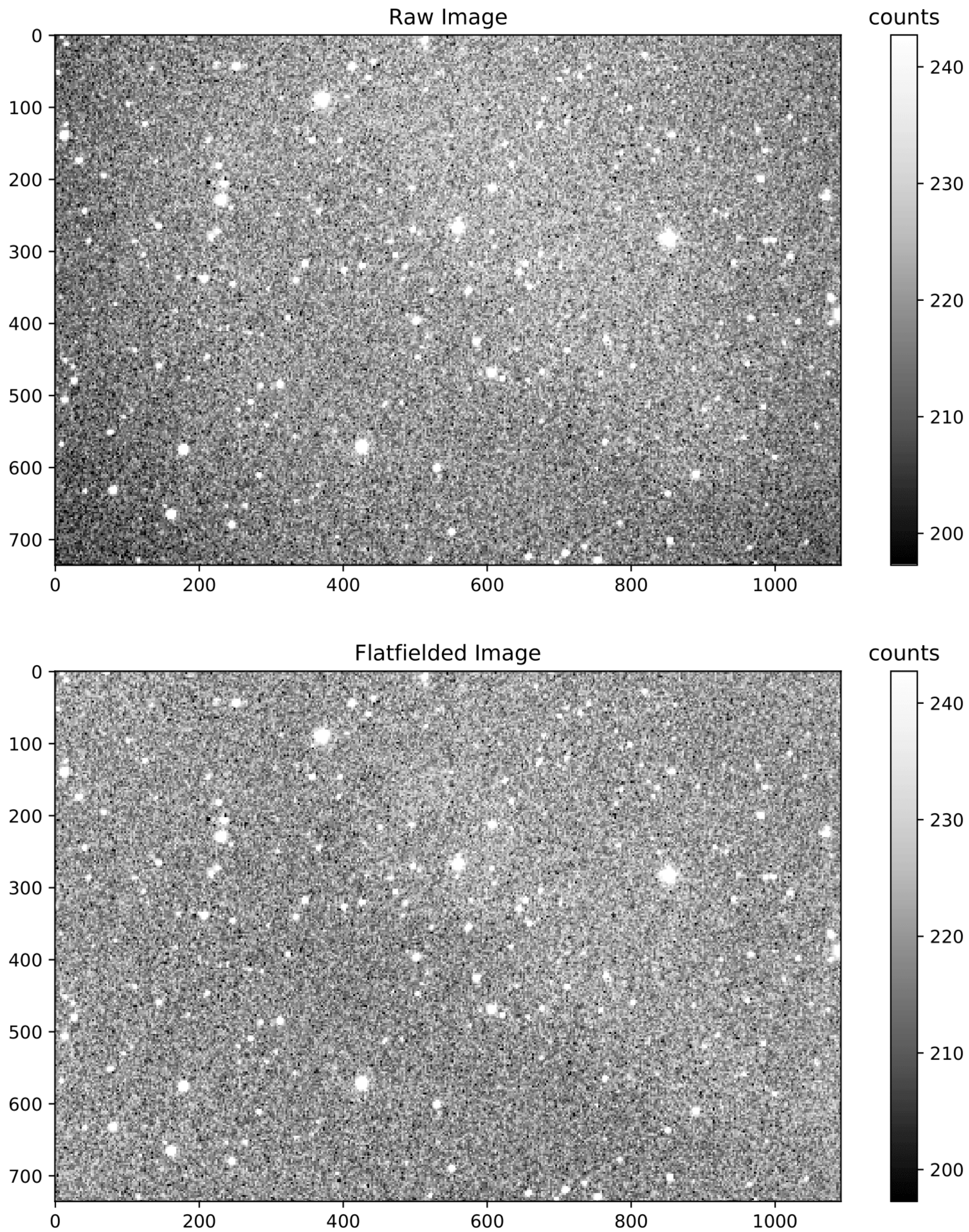
The next part was to produce flat field images. As mentioned when flat field images are overlaid with a normalised image it creates a photo that doesn't differ in brightness too much. Combining the flat field images and normalises them produces a fairly accurate image. However, doing a median combined normalised flat creates a smoother version of the previous image. This is show below in figure 2:

Figure 2: Difference between mean combined and individual normalised plots.



After creating this image, combining the raw image data set and combining the normalised flat images creates the ideal calibrated image to do analysis on. This works by taking the raw image data and dividing it by the combined normalised flat field image. Coding this program to do this reduces vignette on the image and also makes the stars that are of key importance more visible in the night sky. This progression in quality of the raw image is show below:

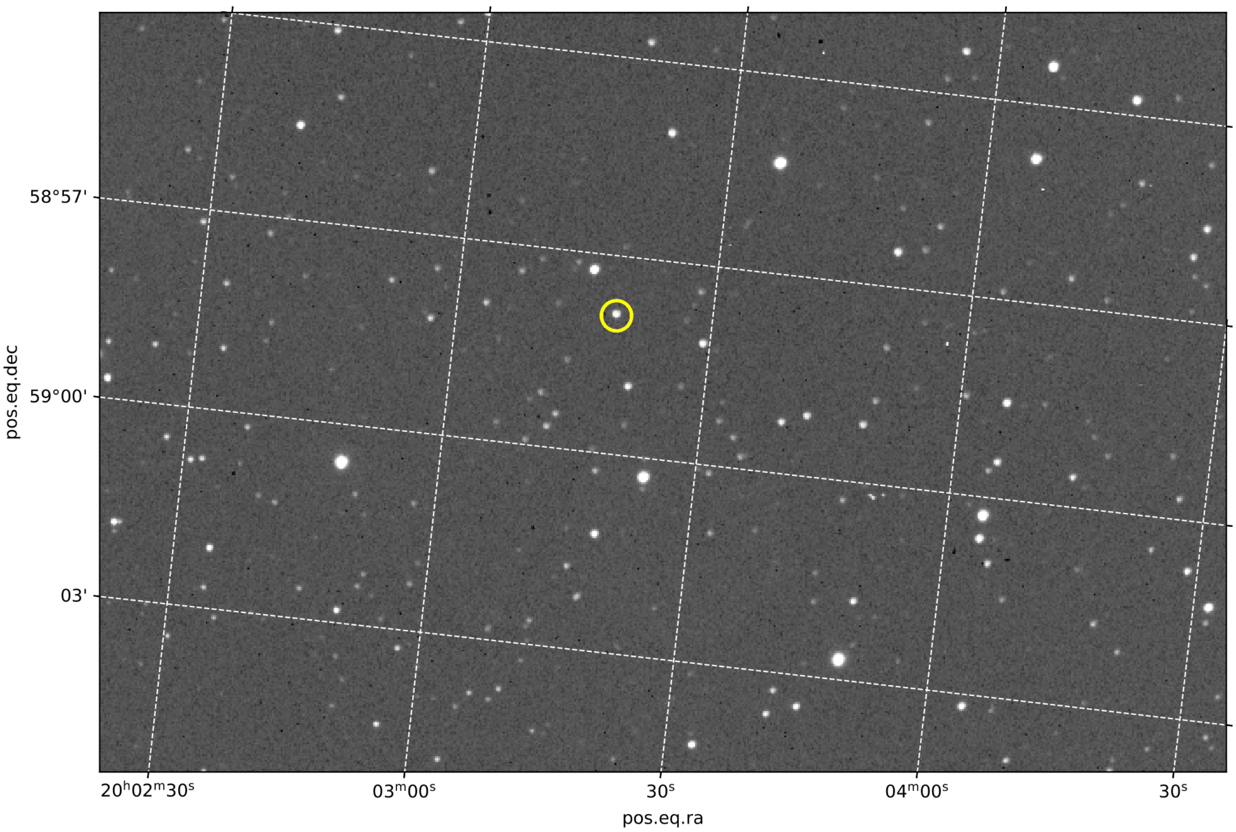
Figure 3: Flat field comparison to raw image



4.3 World Coordinates

The last stage of the calibration of images is to plot the world coordinates onto the flat flied image. Doing this will make it easier to understand what star is which in the image. Doing this gives the plot axes of ascension and declination. In this image shown below a circle highlighting a random star is shown as well to check if the code is working properly to gain access to a legend to comment on what star is what. Figure 4 shows the final calibrated image:

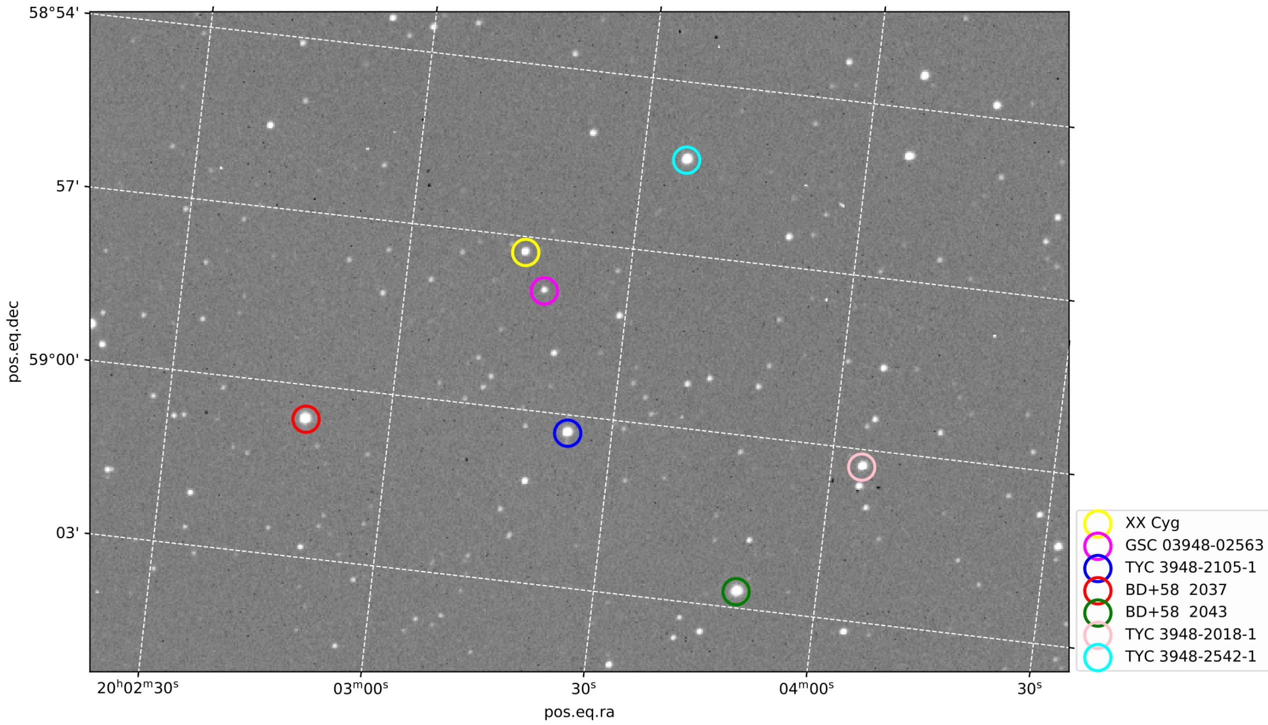
Figure 4: One star in the night sky



4.4 Photometry

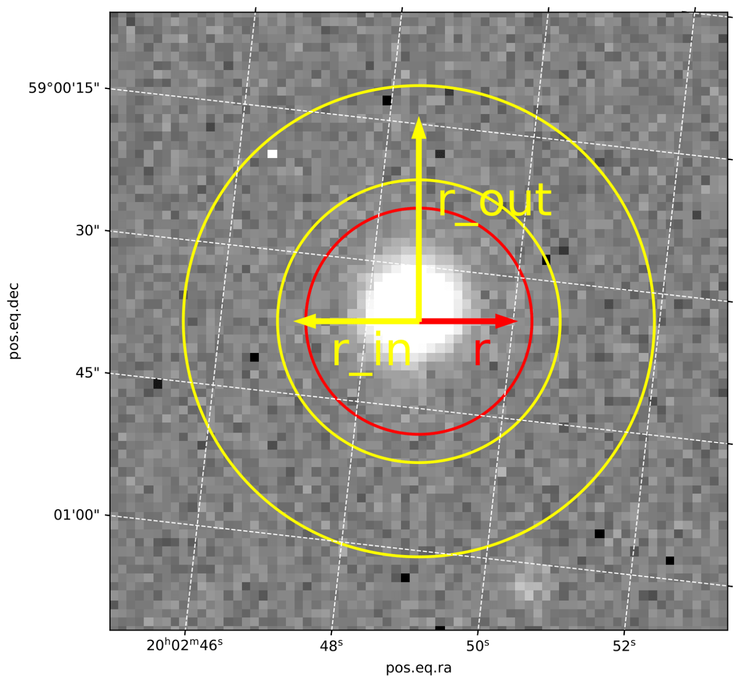
It is first necessary to highlight the positions of each star in the calibrated image for this section of the results. Picking stars that were in the image and not close to the edge create an accurate set of data at the end of the analysis. In the photo it also shows where XX-Cygni is located. This means that the first important step has been completed. The experiment can now be narrowed down at the end to find the distance for this star. Figure 5 shows the image with the known and important stars highlighted on it:

Figure 5: Multiple stars in the night sky



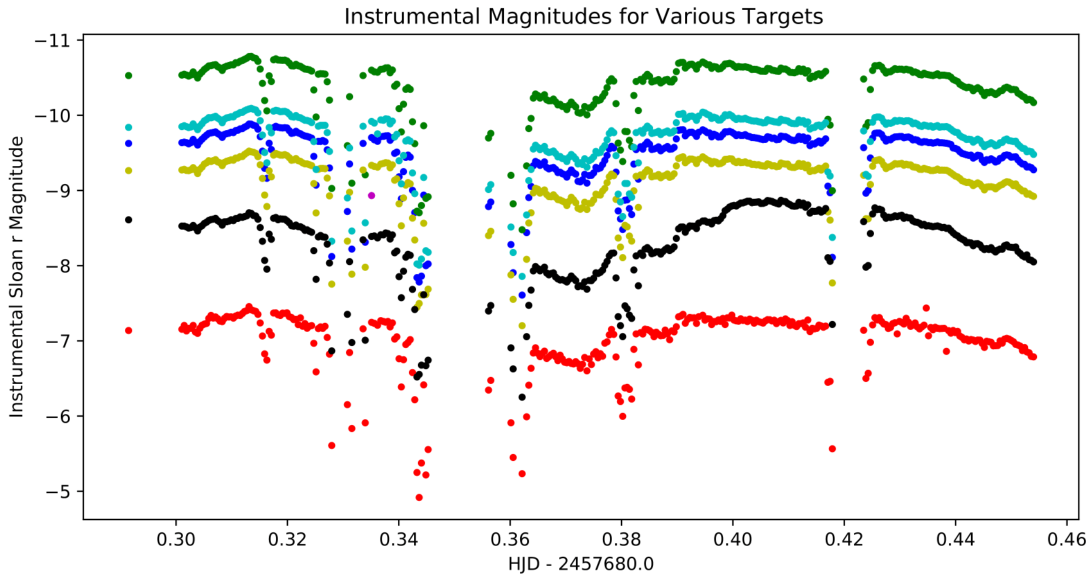
The process of aperture now begins. In the method section of the report it was explained that aperture photometry is being used. The image below shows this in practice, with two circles you can calculate the aperture of just the star needed:

Figure 6: Aperture of one star



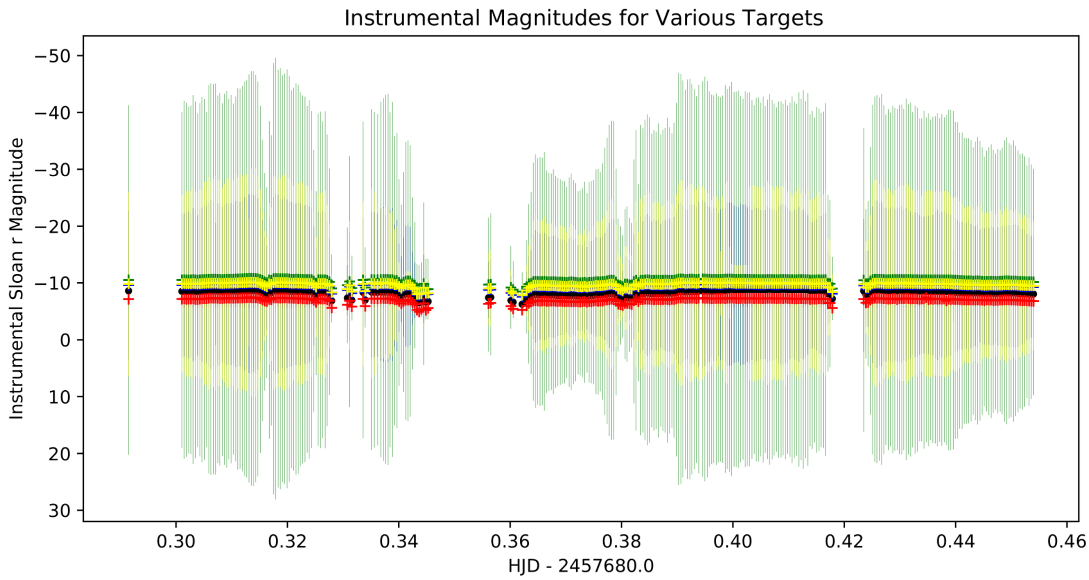
After doing this again for the other stars in the image it is time to do instrumental magnitudes. This shows how volatile magnitudes can be before you calibrate the stars brightness. The meaning of these graphs will be discussed in detail later on in the report. In figure 7 it shows instrumental magnitudes for each of the stars highlighted in the calibrated world coordinate image:

Figure 7: Instrumental magnitudes for multiple stars



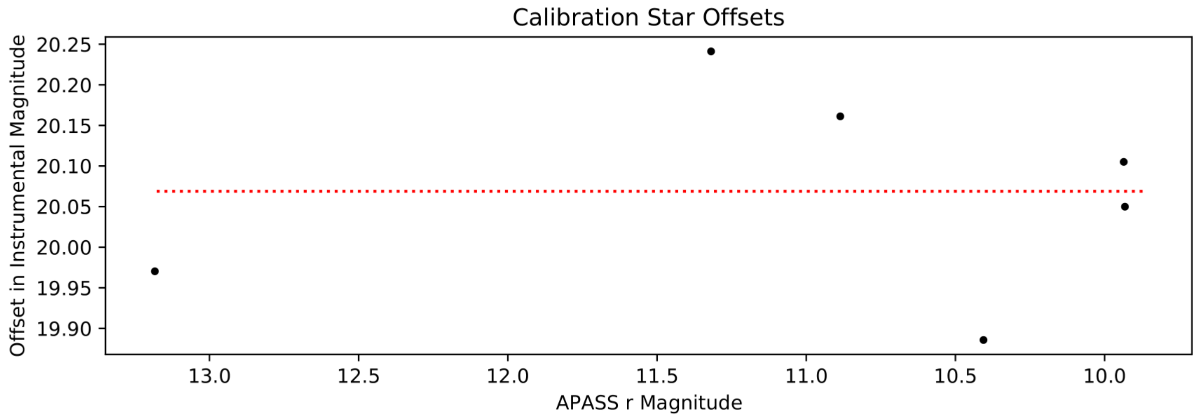
In this figure error bars have been placed for instrumental error and flux error on figure 7. The accuracy of these error bars will be discussed in the error analysis section but something is creating very large error bars resulting in this graph shown below:

Figure 8: Error bars for Instrumental magnitudes for multiple stars



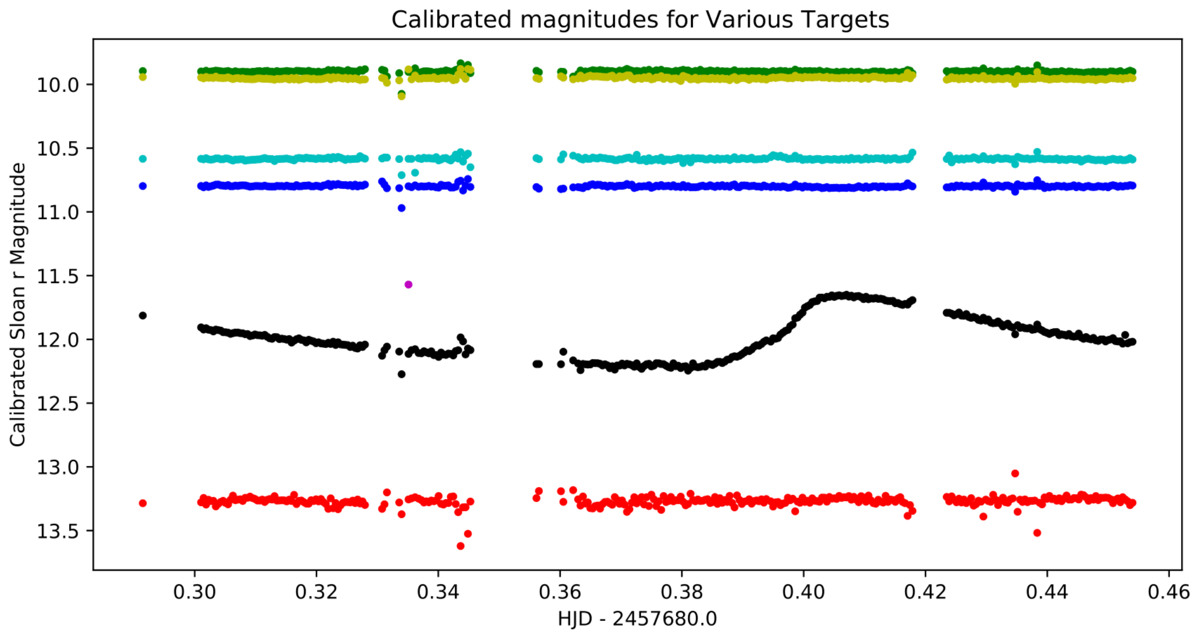
The next step in this photometry section is to find the calibration offset. This will then allow the instrumental magnitude figure to be calibrated. This in turn will also make it clear which one is XX-Cygni. The calibration offset is calculated and is shown here in figure 9:

Figure 9: Calibration offset



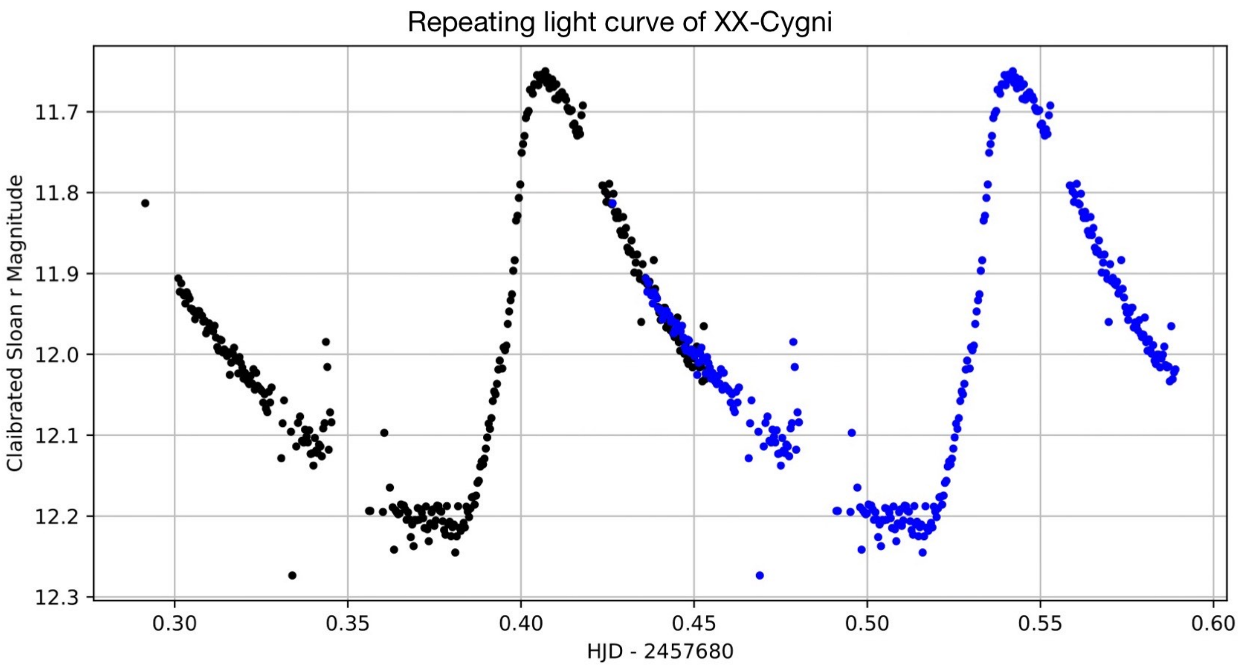
Using the calibration offset figure 10 shows the instrumental magnitude calibrated. It is clear that the black line is XX-Cygni because of how it isn't a straight line. This shows the change in magnitude due to the pulsing nature of this standard candle.The curve upwards shows when the star increases in brightness and the decline on the plot shows the decrease in brightness. Figure 11 shows these details:

Figure 10: Calibration magnitudes



The last plot to be made is the light curve of XX-Cygni. Repeating the curve twice shows the nature of the star and the way to repeat it is to find the period. In this case the period was calculated using a reading from a data base and compared it to a rough value when trying to match the plot lines up. The period value turned out to be around 0.135 days. The image in figure 11 clearly highlights the trend of magnitude for this certain star and in the final part of the results section the distance can be calculated using this. See figure 11:

Figure 11: Light curve for XX-Cygni



4.5 Calculating distance

Using the plots created distance from XX-Cygni to Earth can be calculated. The first step is to find the average apparent magnitude for XX-Cygni. When calculated a value of '11.987' is discovered. The next step is to put this into the equation for Cepheid variable stars. The process and the equation is shown below:

$$Mv = -2.76 \times (log_{10}(P) - 1) - 4.16 \tag{3}$$

Substituting the period calculated above and the average apparent magnitude for XX-Cygni the absolute value of 1 is found.

The final step is to calculate the distance in parsecs from these values obtained. The equation used is shown below:

$$D = 10^{(m_v - MV + 5)/5} \tag{4}$$

Substituting these values in I get a distance of 1573.79 Parsecs.

4.6 Supplementary Information

When doing this experiment extra research was done on XX-Cygni. In the research process it was discovered that XX-Cygni is not only a Cepheid variable star but a delta Scuti variable star. This means that it is smaller than a standard variable star. Furthermore, after finding out this information, it was discovered that there are equations that are used for only delta Scuti variable stars. This will allow for a more accurate representation of the distance between Earth and XX-Cygni. This equation is:

$$Mv = -2.76 \times (log_{10}(P) - 1) - 1.34 \tag{5}$$

This value comes out to 1.219 W

After this using equation 4 the numbers found are plugged into the equation and a value of 1424.34 parsecs is calculated. This is 149.44 parsecs closer to the actual distance which is 1162.9 Parsecs.

4.7 Conclusion of Results

Concluding this results section, the data discovered is laid out below:

1. Standard formula for Cepheid variable stars gave the result of 1573.79 Parsecs
2. Delta Scuti variable star formula gave the result of 1424.34 Parsecs
3. The actual theoretical distance is 1162.9 Parsecs.[9]
4. Delta Scuti formula is 149.44 Parsecs closer so this value will be used.

5 Error analysis

Error analysis for this experiment requires different analytical processes. All of these combined together create an uncertainty value which can show whether or not the value from this experiment matches theoretical data.

The first method is the Poisson process. Light that enters the CCD camera at any given time interval will vary as it is a random process when light enters the sensor. The trend this random process follows is a Poisson distribution which looks like this:

$$P(N) = \frac{\mu^N}{N!}e^{-\mu} \tag{6}$$

where P(N) is the probability of measuring N counts and μ is the mean photon count. The uncertainty in this method is proportional to the square root of the number of counts received[4].

As well as this uncertainty there is error in the flux calculation for the CCD camera. For aperture photometry there is a specific equation that is used. This equation includes the Poisson distribution described in the paragraph above. Equation 7 shows the flux error uncertainty:

$$ERROR = \sqrt{(FLUX \times EPADU + AREA) \times (1 + (\frac{AREA}{NSKY}) \times STDEV^2)} \tag{7}$$

where flux is the value calculated above, EPADU is the conversion factor for the CCD camera that equals around 1.3 electrons per ADU the camera used. The area is the aperture area for the camera. NSKY is the number of pixels in the sky annulus and STDEV is the standard deviation.[4]

The first term is the Poisson uncertainty and the second term is the uncertainty in the background sky counts scaled to the aperture area compared to the number of pixels in the sky.

The flux error can be propagated to the magnitude equation using this formula shown below[4]:

$$MERR = \frac{2.5}{log_e(10)} \times \frac{ERROR}{FLUX} \tag{8}$$

5.1 Conclusion of Error Analysis

The error in flux was found to be:

FLUX ERROR	MAGNITUDE ERROR
±614.84	±2.93
±603.30	±0.93
±620.32	±8.98
±637.50	±19.9
±604.75	±20.01
±592.60	±11.35

Table 1: Flux and Magnitude error

6 Discussion

In this experiment everything required to solve the problem at hand was performed carefully, with accuracy and precision. Calibrating the stars location from raw images taken from the Exeter telescope went smoothly and the photometry section produced the relevant graphs to be able to calculate the relevant data. Further research into the star allowed the discovery of additional equations that can make the final results even closer to the theoretical values. Each individual graph and piece of code worked together to create a cohesive method to calculate the distance between XX-Cygni and Earth. Magnitude calculations and the realisation that database units were different to the units being created in the code allowed for a more in depth analysis as multiple steps were used to understand the premise of this challenge.

With any experiment there is always things that didn't go well and could be improved. With this report the main thing was the error analysis. There was an incredibly high uncertainty in the flux. If there was more time a calculation of the the distance uncertainty would make this report feel more whole. It would end the report very nicely. In this instance it didn't work but for the future there is definitely places to improve. From looking over the data already there is perhaps an anomalous aperture star that had two stars in it's aperture ring. If gone unnoticed it can severely effect the outcome of data. Having two stars in one aperture calculation will make the flux evidently bigger than what it should theoretically be.

Another improvement to this experiment ,to make the data more accurate to the final result, would be to calculate the period manually. Using results from previous plots, the period for that specific part of time for the star can be calculated. Finally, and the most important improvement would be to repeat this experiment for multiple nights. Repeating the experiment not only improves reproducibility of the method, it can also make clear what results could be a hindrance to the final results. Finding an average distance from multiple distances from different nights would really create a well researched result. This paired with error bars on every graph would give peer reviewers and external bodies an idea of where the experiment took into account the errors. In this experiment, it was only done for the instrumental magnitude plot.

7 Conclusions

To conclude, after calibrating the image, plotting world coordinates, defining each stars location and performing photometry on XX-Cygni, the distance it is from Earth was finalised. With error analysis and a discussion describing what could be improved the experiment went well. It shows that with more time it could be even more successful. The final result of this experiment is 1424.34 Parsecs with the theoretical database result being 1162.9 Parsecs.

References

[1] University Of Exeter Physics, *Photometry Cookbook 1*

[2] University Of Exeter Physics, *Photometry Cookbook 2*

[3] University Of Exeter Physics, *Photometry for XX Cygni*

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[5] http://www.wvi.com/~rberry/astronomy/xxcygni/xxcygni.htm(17thJanuary2023)

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[8] https://www.techtarget.com/searchstorage/definition/charge-coupled-device#:~:text=A\%0charge\%2Dcoupled\%20device\%20(CCD)\%20is\%20a\%20light\%2D,light\%20captured\%20by\%20that\%20pixel.(21stJanuary2023)

[9] https://simbad.cds.unistra.fr/simbad/sim-idIdent=xx+cygni&NbIdent=1&Radius=2&Radius.unit=arcmin&submit=submit+id (17th February 2023)