Light Curve and Spectroscopic Analysis of Cygnus X-1

We present an estimate for the orbital period of the black hole binary system Cygnus X-1/HDE 226868.The SBIG STL-6303 0.4m telescope from the Las Cumbres Observatory (LCO) was used in pair with a Bessel B filter to observe the binary system on 8 separate days. Performing photometry using astropy on the data returned from the observatory allowed for the blue magnitude to be found for each of the days. Plotting a sinusoidal line of best fit on the data using scipy's optimize function then gave us a value for the orbital period of the system which was found to be 5.515 ± 0.147 days . This value is within an error bar of the accepted value of 5.6 days [3]. Additionally, the three observation ID's 3814, 8525 and 9814 [6] from the Chandra X-Ray Observatory were used to create a light curve from the X-rays arriving due to the accretion disk of the black hole [10].

I. INTRODUCTION

Cygnus X-1 is an X-ray source in the constellation Cygnus and was the first black hole to be confirmed. Discovered during a rocket flight where Geiger counters picked up a signal emanating from a blue supergiant star orbiting an invisible, massive object, it lies a distance of about 7200 light years from Earth and is an estimated 21 solar masses. It's 'invisibility' combined with the huge estimated mass makes it an extremely likely candidate for a black hole [4]. As the two bodies orbit each other, the stellar wind of the supergiant fuels the accretion disk of the black hole, resulting in matter being heated to millions of degrees, resulting in emitted X-rays [10].

The blue super-giant orbiting the black hole is called HDE 226868 and is a type O9.7 star[9]. The magnitude of the star varies about 0.04 in amplitude in B-magnitude over a 5.6 day period [7]. This blue star's variability in magnitude in a relatively short time frame led to it being a good candidate for the creation of a light curve

The importance of knowing the orbital period is seen when combined with the knowledge of either the radius of orbit or mass for a well studied system such as the Earth and sun.

$$T^2 = \frac{4\pi^2}{GM_{sun}}a^3 \tag{1}$$

This is known as Kepler's third law, where T is the period of orbit for the Earth and a is the semi

major axis since the orbit in this case is elliptical. By knowing the period of orbit, the unknown mass of the object that you are rotating around or radius of orbit(semi major axis in the elliptical case) can be solved for.

Light curves provide an effective way of finding this period of orbit, as we show in this paper. By plotting the apparent magnitude vs time, a period of orbit can be extracted by seeing how long it takes for the magnitude to vary one full period. This is the method that is used in this paper to provide an estimate for orbital period of this black hole binary system.

Additionally, the large flux of X-rays makes this system a very well studied object by the Chandra X-ray observatory. The Chandra X-ray observatory was launched in 1999 aboard the Space Shuttle Columbia and was designed specifically to observe high energy regions of space[1]. Due to the blocking of X-rays by Earth's atmosphere, this telescope orbits the Earth in space in order to be able to detect them. Due to the high interest in Cygnus X-1 leading to a lot of externally available data, creating a light curve of the X-ray flux from this source was done in this paper as well.

II. METHODS

To obtain an orbital period estimate for the black hole binary system, we created a blue band light curve of the magnitude of the star that is orbiting the black hole. The telescope used to observe the star was LCO's SBIG STL-6303 0.4m telescope paired with a Bessel B filter. These telescopes are located in multiple observatories around the world to allow for more chances to make observations of objects that may not be visible from certain locations. The number of Exposures taken was 50 with an integration time of 4 seconds. This integration time was chosen by using the LCO exposure time calculator to estimate the maximum exposure time we could use without over saturating our images. The idea behind using the Bessel B filter was that since the star HDE 226868 was a blue supergiant that most of the light emitted would be in the blue band.

The LCO visibility tool was then used to find the times that the system was visible over a 9-day period, and an observation request was then submitted for the days of May 18th - 26th, where we were hoping to obtain two measurements per night, but only obtained data for the 18th - 25th, with only a few of those days returning two of the measurements per night. This fortunately did not have a huge impact on our analysis.

The data returned by LCO was received in the form of FITS files with 50 fits files arriving per observation(the amount of exposures). We chose to use the raw images instead of the BANZAI

processed images. The BANZAI processed images have calibrations performed on the raw images such as bad-pixel masking, bias subtraction, dark subtraction, etc, but we did some of these calibrations manually using astropy. These 50 fits files were opened in Astro Art and were averaged into one FITS file for the observation using the pre-processing tool and auto alignment. An example of one such FITS file is shown in Figure 1. These images were then calibrated to be able to calculate apparent magnitude in Python using the following equation:

$$M_{sky} + 2.5 \log_{10}(N_{aperturesum}) = ZP \tag{2}$$

where M_{sky} is the magnitude of the star as seen in the night sky(the apparent magnitude). The M_{sky} values for the reference stars were found through sky-map.org, a website that contains data of positions and basic characteristics of the night sky such as magnitude. $N_{aperturesum}$ is the sum of the pixels of a circular part of the image with a defined radius. This sum was then used to get the number of photons coming from a single star. ZP is the zero point of our image and is found by subtracting the calculated value of the magnitude in the image $m = -2.5 \log_{10}(N_{aperturesum})$ from M_{sky}(the known value). So ZP is the difference between the value of the magnitude of the star in the image and the known value. An example of the apertures used as well as the reference stars that we chose is shown in Figure 2.

Figure 1: FITS file image for the day of May 18th, opened in ds9. The star HDE 226868 is seen in the center of the image, the star close by to the left of it is unrelated.
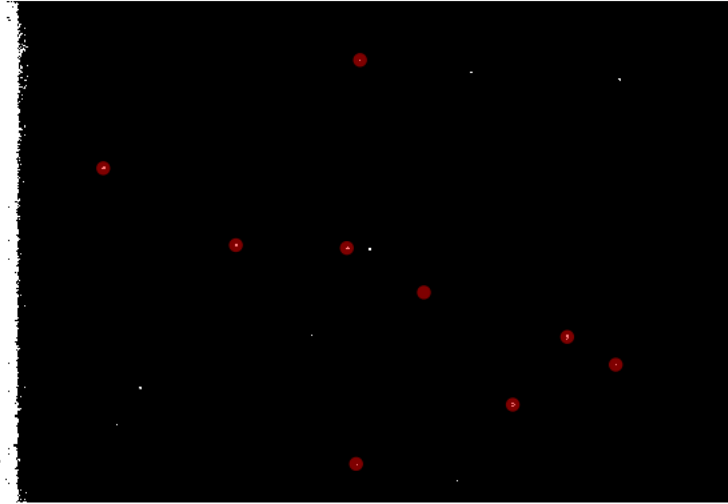
Figure 2: Shown are the apertures used for the 9 reference stars. We made sure to use the exact same 9 reference stars for each observation.The aperture sum sums up all the pixels to get the number of photons arriving from the star.

In order to make a calculation for the magnitude of our target, the ZP for the image must be calculated. This was done by using 9 of the brightest stars in each of our images where we made sure to use the exact same 9 stars for each of the observations. The reference stars used were the same for each observation to ensure that the ZP of the observations are relatively similar and that the error is minimal due to different calculated ZP. To find the ZP for the image, the average of the ZP found through equation 1 for each of the 9 reference stars was taken since they aren't exactly the same.

To find $N_{aperturesum}$ the x and y coordinates of the 9 reference stars for that image were found through AstroArt and were input into Python. Apertures were then created around the stars using the photoutils.aperture library in Python where the sum of the pixels and hence the number of photons arriving could be found.

Once the average ZP of the image is found, the image is calibrated and we can calculate the magnitude of our object. The value $N_{aperturesum}$ for our object was found and $2.5\log_{10}(N_{aperturesum})$ was calculated and subtracted from ZP as can be seen in equation 1. This gave us a value for M_{sky} for our object.

The FITS files for the observations contain in them the Modified Julian Date which is a way to number the days in a consecutive fashion. These times are stored in the header of the FITS file and is labeled 'MJD_OBS' where we could then use these times to make a plot of magnitude vs. time

This process was repeated for each of the 13 images to find the time of the observation and the magnitude of our object at that time and the times and magnitudes of our object were plotted and were fit with a sinusoidal line of best fit using scipy. A sinusoid was a good approximation since the eccentricity of the system is found to be 0.018 [8], which means that we can approximate the orbit to be circular.

Scipy's optimize curve fit function was then used to return the best possible parameters to fit for our data in the following equation

$$A\sin(\omega t + \phi) + C \tag{3}$$

where ω is the angular frequency, A is the amplitude ϕ is the phase offset and C is the amplitude offset. The period can be extracted using $T = \frac{2\pi}{\omega}$.

In order to create an X-ray lightcurve for the system, data from the Chandra X-ray observatory was used. The three observations chosen, 3814,8525, and 9814 were chosen since their phases appear to overlap [6], which is important since there werent any observations that were on consecutive days. For example the observation 3814 is approximately 50ks, or about 14 hours along, not enough to see a full dipping in the orbit. Assuming a 5.6 day orbital orbit, we should be able to see some dipping with three different days of data if the phases overlap. The Chandra X-ray observatory has their own software to analyze their data, and I followed their data analysis guides to create the light curve [2]. The data gets downloaded using CIAO, and gets calibrated by using a command called 'chandra_repro' on the data, which applies the latest calibrations that are constantly being updated by the observatory onto the data. The chandra data comes with a lot of FITS files, but the only one used to create the light curve was the evt2.fits file, which is a list of events that are considered suitable for data analysis. The light curve was created by first creating a region in the data using ds9 of the source, in this case Cygnus X-1. This is shown in Figure 3 by the
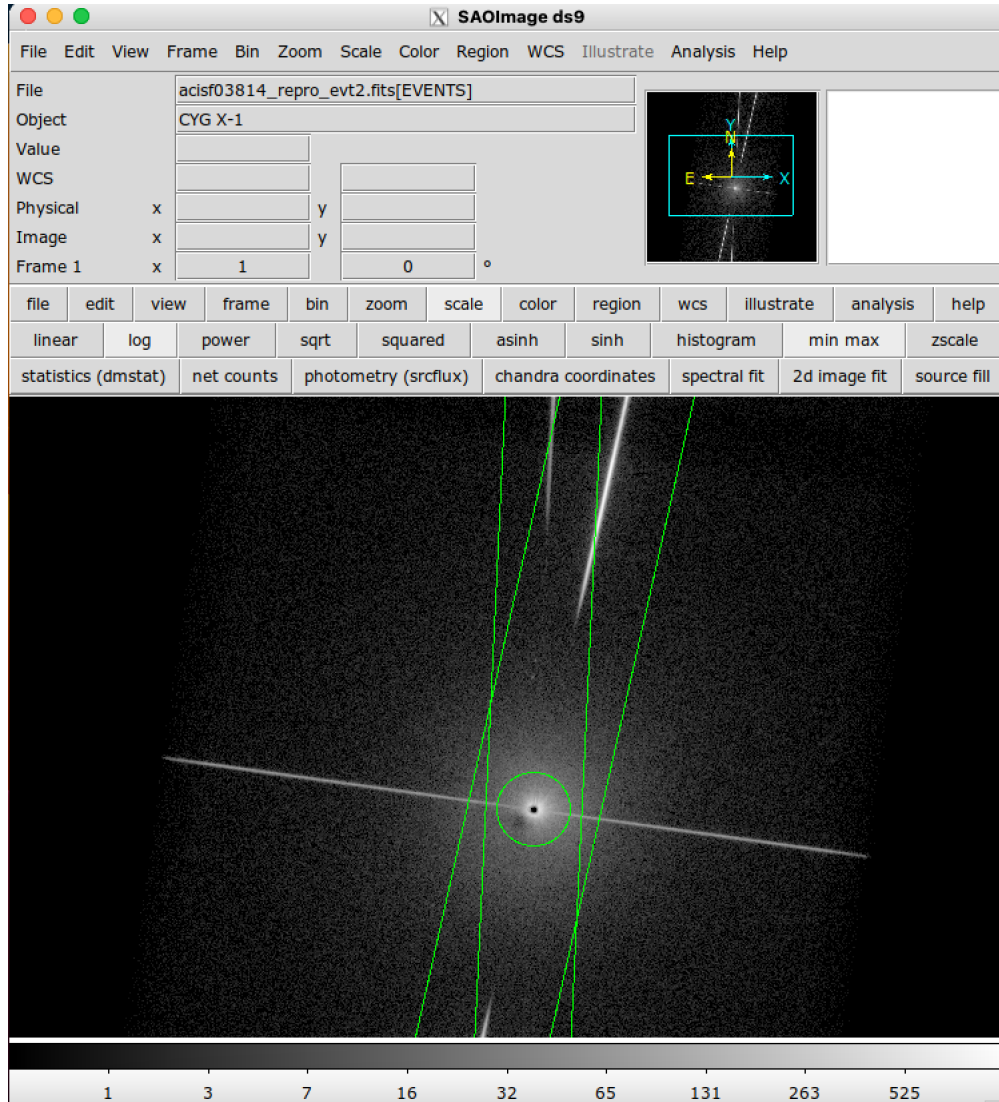
Figure 3: Example of regions used to create light curve of X-ray data, shown by green lines.

green lines. The evt2 file comes automatically with a source region, which is what was used. The command dmextract was then used to extract the light curve of the observation, and this process was repeated for the three observations that we chose.

III. RESULTS

The calculated magnitudes are shown in Table I. The error is calculated by taking the standard deviation of the ZP calculated for the nine reference stars on each observation

$$\sigma = \sqrt{\frac{\sum(ZP_i - \mu)^2}{N}} \qquad (4)$$

where ZP_i is the zero point calculated for one reference star, μ is the average of the 9 zero points calculated of the reference stars, and N is the total number of reference stars(9).

The light curve is shown in Figure 4. The magnitudes have very large error bars due to the standard deviation of the ZP, each reference star had slightly different values for their ZP,resulting in a fairly high standard deviation. Some possible reasons for this could be that the stars we chose for reference were different in magnitude on a given day than what sky-map was giving us, leading to higher or lower ZP's compared to the other reference stars.

The line of best fit for our data was

$$-0.046 \sin(1.139t - 8365.845) + 9.41 \tag{5}$$

As can be seen, by converting the angular frequency to period, we obtain $T = \frac{2\pi}{1.139} = 5.515$. Our variation in magnitude is given by the absolute value of the amplitude of the sine wave, 0.046. The error in this calculated value was ± 0.185, so while our value agrees fairly well with the predicted value of 0.04, our error in this calculated value is too large to be conclusive.

The magnitudes that we used for the reference stars were the apparent magnitudes given in sky-map.org, however, we realized that we had used a Bessel B filter, which means that we would need to find the blue magnitude of the reference star. We did not know how to go about finding the blue magnitudes of the stars, so we just stuck with the apparent magnitudes. The calculated orbital period of our object shouldn't be affected much by this.

The blue magnitude of HDE 226868 is known to be 9.72 [5], and we obtained values that are brighter than this. Again, this is most likely due to us using the apparent magnitude of the reference stars instead of using the blue magnitude. Blue magnitudes would have given us dimmer values for the reference stars(larger M_{sky} values), leading to larger ZP values, which means we should calculate larger values of magnitude for our object if we were to use blue magnitudes for the reference stars instead.

The calculated orbital period for the black hole binary system was 5.515 ± 0.711 days. The accepted orbital period is 5.6 days [3], so our calculated value agrees fairly well.

The error in our calculation of the orbit comes from taking the square root of the diagonal of the covariance matrix that comes with the parameters that scipy returns when you find a line of best fit. The diagonal of the covariance matrix gives the variances, and the square root gives the standard deviation. Since the sinusoid that we fit to our data returns angular frequency and not period, the error in the period must be calculated from the error in the angular frequency using

the following equation:

$$\frac{\delta\omega}{\omega} = \frac{\delta T}{T} \tag{6}$$

where $\delta\omega$ is the uncertainty in the angular frequency and δT is the uncertainty in the period.

The X-ray light curve is shown in Figure 5. The three observations are plotted on the same axis to show the overlapping in phases. The dipping seen in count rate over time can be explained by the stellar wind that is powering the accretion disk of the black hole. This stellar wind has inhomogeneities, where some clumps of colder material in the gas pass through our line of sight, resulting in dipping in the count rate [6].

Shown in Figure 6 are the count rate vs energies. Observation 9847 shows the highest number of X-rays with energies in the range 1.6-2.7 keV range, which corresponds to sulfur and silicon absorption lines[6].

Table I: The calculated magnitudes for each observation.

Modified Julian Date	Apparent magnitude
60083.0591203	9.339 ± 0.314
60083.0878574	9.343 ± 0.317
60084.0506164	9.389 ± 0.265
60084.0878528	9.340 ± 0.327
60085.5877991	9.449 ± 0.254
60085.0564357	9.428 ± 0.286
60085.0924436	9.425 ± 0.308
60086.4494546	9.400 ± 0.245
60087.5437068	9.457 ± 0.236
60088.168957	9.392 ± 0.302
60088.5877895	9.418 ± 0.258
60089.0878462	9.335 ± 0.331
60090.4327304	9.459 ± 0.242

IV.   DISCUSSION

Our light curve for the LCO data gives us an orbital period that agrees fairly well with the accepted value of 5.6 days. However, the calculated magnitudes have relatively high errors, meaning that in order to get a better line of best fit, we would've had to have done many more observations over a very large time period. While this orbital period agrees fairly well, our measurements are probably not very precise due to the large error bars in our calculated magnitudes.
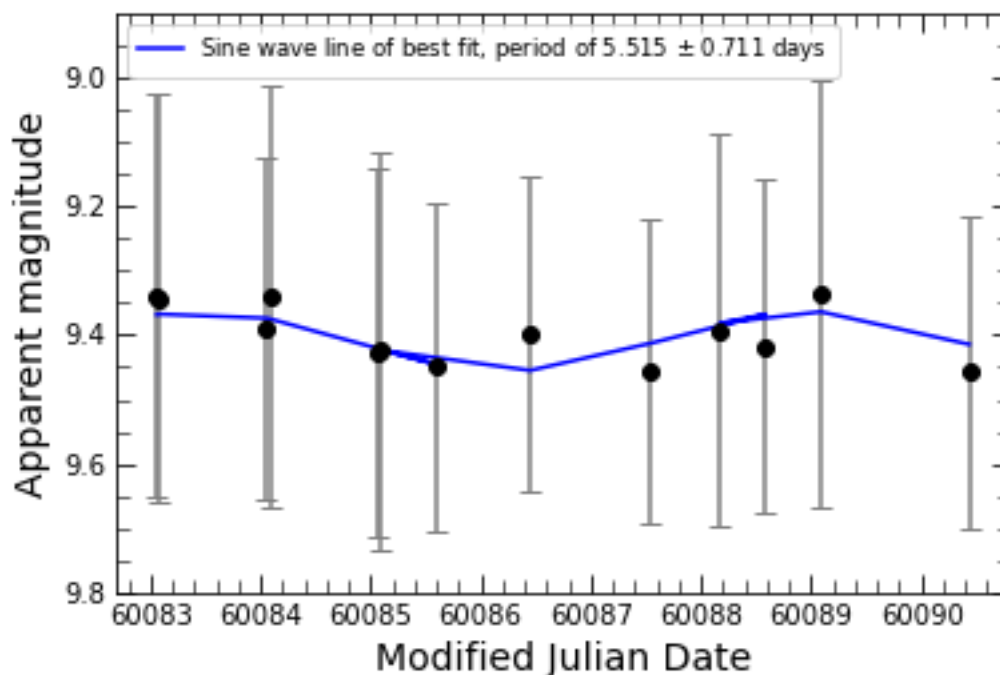
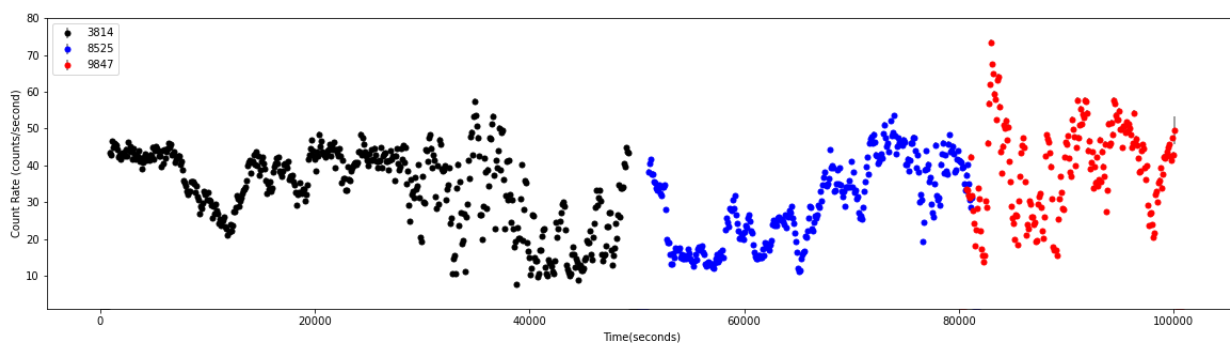Figure 4: Light curve created using data from the LCO telescope.

Figure 5: Chandra X-ray data light curve.

Our measurements could've been improved if we did not use a filter. For some reason we were under the impression that we had to use a filter, but for our purposes it really wasn't necessary and was even a hindrance for us since it ended up messing with the magnitudes that we were supposed to use vs the values that we ended up using for our reference stars.

The limitations imposed of having not a lot of time with the LCO telescope also leads to errors, because ideally we would've had multiple observations a night to get a better average magnitude for that day.
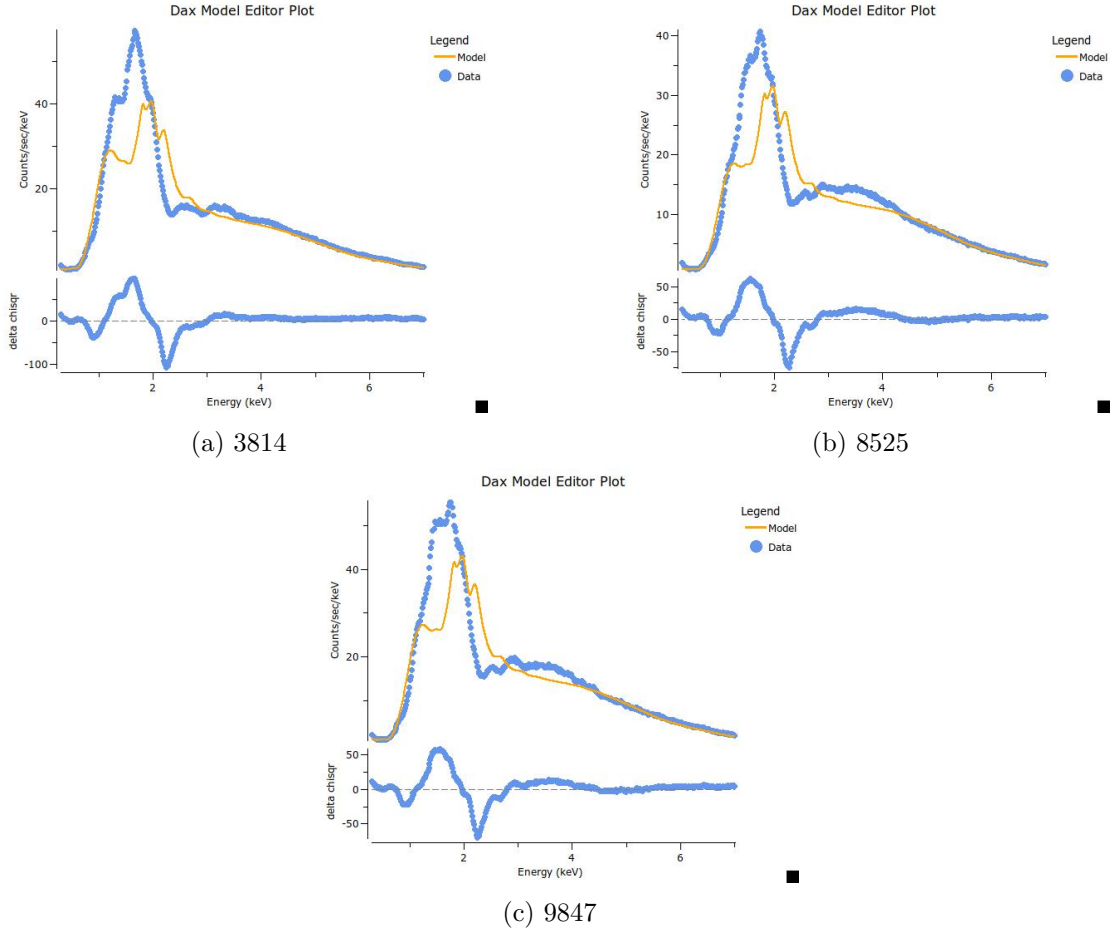
(a) 3814

(b) 8525

(c) 9847

Figure 6: Count rate of the energies of the X-rays that re observed.

Since the standard deviation, our largest source of error, is proportional to $\frac{1}{\sqrt{N}}$ where N is the number of reference stars used, if we had used many more reference stars, we could've gotten the error bars of our measurements down.

The analysis done with the Chandra data was difficult due to the learning curve that came with using the software. Learning how to reprocess the data and extract the the light curve was very time consuming, so understanding the implications that come with the data was something that I would've liked to have understood better if I had more time since the prerequisite knowledge needed to understand what some of the data returned does is fairly large.

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