Orbital Period and Light Curve Analysis of Cygnus X-1

An estimate is calculated for the orbital period of the black hole binary system Cygnus X-1/HDE 226868. Over the course of eight days, the SBIG STL-6303 0.4m telescope from the Las Cumbres Observatory (LCO) was used in pair with a Bessel B filter t o observe the binary system. A blue-band magnitude is found for each day by utilizing photometry using Astropy on the data returned from LCO. Using Scipy's optimization function to plot a sinusoidal line of best fit then provided a value for the orbital period of the s ystem. This is found to be 5.515 ± 0.147 days. This value is within one error bar of the accepted value of 5.6 days [1]. Furthermore, using the Chandra X-Ray Observatory's observations with observation IDs 3814, 8525 and 9814 [3], a light curve was created from the X-rays arriving due to the accretion disk of the black hole (Cygnus X-1).

I. INTRODUCTION

Cygnus X-1 is an X-ray source located in the constellation Cygnus and was the first black hole to be discovered. It was found using the signal from a pair of Geiger counters aboard a sub-orbital rocket. Cygnus X-1 lies about 7200 light years away from Earth and is about 21 solar masses.

Cygnus X-1 is part of a binary system, where a supergiant variable star called HDE 226868 is in orbit with the black hole. As the two bodies orbit each other, material is pulled from the supergiant and accelerated in the accretion disk of the black hole. The rapid and superheated material emits X-rays as a result, which can be detected from Earth.

The system's short period of magnitude variability (course of a few days) makes it a good object to study for creating a light curve. Light curves are useful in finding certain characteristics of the target, such as its magnitude variability, angular frequency, and period. This paper will cover our steps in producing a suitable light curve using apparent magnitude of our target (Cygnus X-1/HDE 226868).

In addition, the binary system also releases X-rays, which can be analyzed using the Chandra archive database. The database stores information on observations done by the Chandra X-ray observatory, which is situated above the Earth's atmosphere. This study also explores the X-ray flux of the Cygnus X-1/HDE 226868 system, and we were able to create a light curve for the X-ray

spectrum as well.

II. METHODS

The first step in obtaining our data was putting in our observation requests for the Las Cumbres Observatory (LCO). Looking at the LCO visibility tool, which indicates when the system would be visible over a nine-day period, we decided to put in observation requests from May 18th to May 26th. After the observation was complete, we noticed that we did not receive an image for the 26th, leaving us with data up until the 25th. For each day, two observations were taken, with each being comprised of 50 exposures, and each exposure being four seconds in length. However, the exposures for the 18th, 19th, and 20th did not return two observations, but rather one. Even with this loss of data, it was not significant enough to skew results or introduce a significant amount of statistical error.

The telescope used for data collection is LCO's SBIG STL-6303 0.4m telescope. The Bessel B-filter was used for the LCO exposure data, which allows wavelengths of blue light to pass through more effectively than other wavelengths, resulting in a blue-band light curve for the magnitude of Cygnus X-1/HDE 226868. We chose this particular filter since the supergiant HDE 226868 emits mostly blue light, and capturing the color band that is most intense would maximize light received from the target and minimize light from surrounding bodies that could potentially create noise.

The data received from LCO is in the form of FITS files, with one file per exposure of our target. Using Astroart's pre-processing and auto alignment tools, we averaged each set of 50 exposures (one observation) into one FITS file. The images were then calibrated and processed in Python to find apparent magnitude using the following equation:

$$M_{sky} + 2.5 \log_{10}(N_{aperturesum}) = ZP \tag{1}$$

M_{sky} is the apparent magnitude of a star, in other words, its brightness seen from Earth in the night sky. The M_{sky} values for the reference stars were found through sky-map.org, a website that contains data of object locations and characteristics, such as magnitude. $N_{aperturesum}$ is the sum of the pixels of a defined radius of some object in an image. This value was subsequently used to obtain the number of photons coming from a particular reference star. ZP is the zero point of an image, and is found by subtracting the calculated value of apparent magnitude ($m =$

$-2.5\log_{10}(N_{aperturesum}))$ from the known value (M_{sky}). This makes ZP the difference between the calculated value of apparent magnitude of a reference star and its accepted value.

For each observation, the same nine reference stars were used as apertures to calculate the number of photons coming from the Cygnus X-1/HDE 226868 system.

One example of an averaged image is shown below.

Figure 1: FITS file image for May 18th. The star HDE 226868 is seen in the center of the image, on the right side.

To determine the apparent magnitude of the target, we first had to find the ZP of an image at hand. Using the exact same nine bright stars in the image as reference stars, we can insure that the ZP across observations would be similar in value, and therefore introduce minimal error. To find the ZP of a particular image, the average ZP was taken of all nine reference stars in that image.

Finding $N_{aperturesum}$, the x and y coordinates of each of the nine reference stars were taken per image through Astroart. Apertures were made around each star using Python's photoutils.aperture library, where are sum of pixels in each aperture was found. This gave a value for the number of photons from those stars hitting the telescope at that moment.

Using the ZP for each image, as well as our object's $N_{aperturesum}$, it became possible to determine the magnitude of our object. Using the equation

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

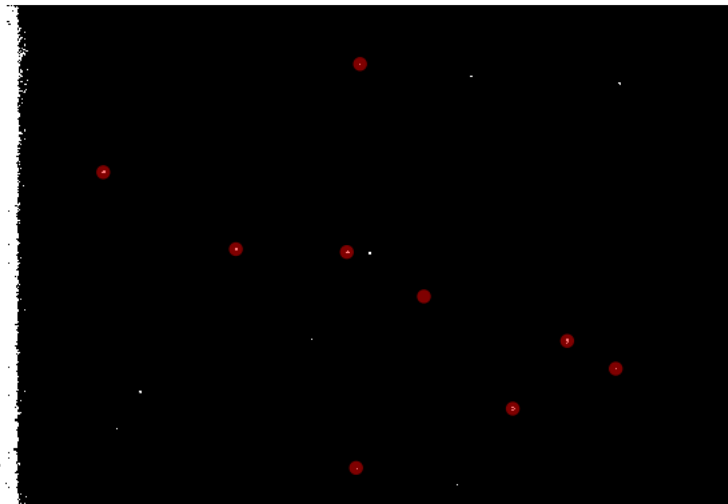we could find a value for M_{sky} of our object, which returns our apparent magnitude.

Figure 2: The shown red circles are the apertures used for the nine reference stars.

In order to plot our data, each FITS file already had the time in which each image was taken according to the modified Julian date system, making time trivial to plot. Using all images and finding each value for M_{sky}, it became possible to create an apparent magnitude vs. time plot which can be seen in the results section. A sinusoidal curve of best fit was found using SciPy, which is the ideal function to use because of the low eccentricity (0.018 [4]) of the binary system, hence an almost circular orbit. SciPy uses the following equation to create the sinusoidal curve, and determines the ideal parameters to use.

$$A\sin(\omega t + \phi) + C \tag{2}$$

A is the amplitude, ω is the angular frequency, ϕ is the phase offset, and C is the amplitude offset.
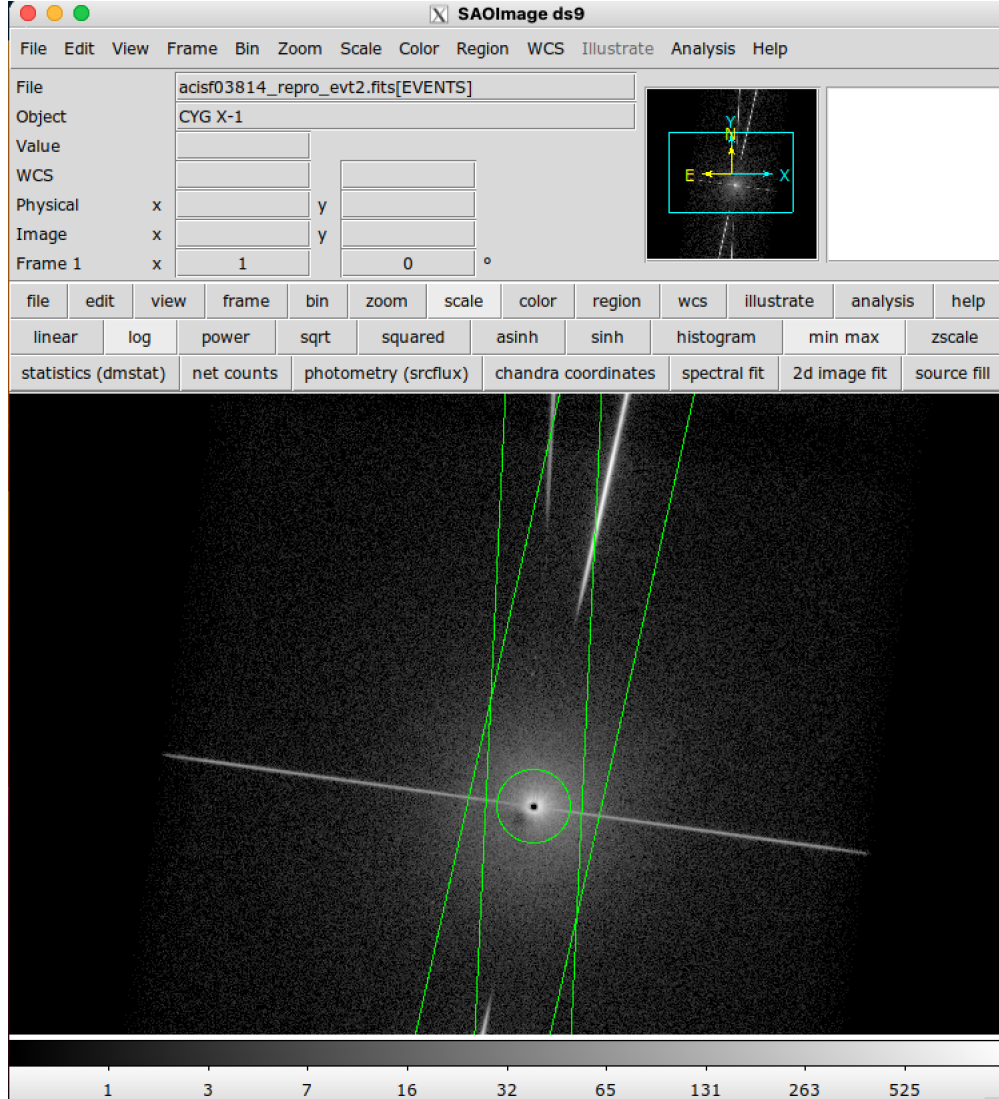
Figure 3: Sample image of image analysis to create light curve of X-ray data. Green lines indicate regions used to produce the curve.

The Chandra archive database is used to make an X-ray light curve for the system. We chose the three observations 3814, 8525, and 9814, as their observations create one contiguous plot with a wide range of phases [3]. The light curve was made using the Chandra X-ray observatory software. The image below shows a sample of image processing done to create the light curve for the Chandra data.

III.   RESULTS

The calculated apparent magnitudes with respect to each day are shown in Table I.

To calculate error, the standard deviation of the ZP (zero point) is taken for the nine reference

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

stars for each day of the observation.

$$\sigma = \sqrt{\frac{\sum(ZP_i - \mu)^2}{N}} \tag{3}$$

ZP_i is the determined zero point for a reference star, μ is the average of the nine zero points of the reference stars, and N is the total number of reference stars, which equals nine in this case.

The light curve is shown in Figure 4.

Due to the high standard deviation of the zero points for each star, the magnitudes have large error bars, as shown in Figure 4. One possible explanation for this is that the chosen reference stars had a different magnitude than what was given on sky-map, resulting in skewed values for zero points.

The curve of best fit for the data is

$$-0.046\sin(1.139t - 8365.845) + 9.41 \tag{4}$$

Converting the angular frequency of the equation above to period, we get $T = \frac{2\pi}{1.139} = 5.515$ days. The error in period is calculated to be ±0.711 days, which agrees fairly well to the accepted value of 5.6 days [1] The variation in magnitude is given by the absolute value of the amplitude of the sine wave, 0.046, which agrees nicely with the predicted value of 0.04. The error in this

calculated value was ±0.185, which is too large of a value to be conclusive.

Due to our usage of the Bessel B-filter, our obtained apparent magnitude values are in fact blue magnitudes of the reference stars. Therefore we need to compare our values to the accepted blue magnitude values of the reference stars in order to make an objective comparison. However due to complications, we used apparent magnitudes which were given on sky-map.org . HDE 226868 has an accepted blue magnitude of 9.72 [2], which is dimmer than what we obtained in our data. This is likely due to the usage of the apparent magnitude of the reference stars instead of using the blue magnitude, as mentioned before.

The error in our calculation of the orbital period are the standard deviations, which arises from taking the square root of the diagonal elements of the covariance matrix (which are the variances) that comes with the line/curve of best fit parameters of SciPy. Because the sinusoidal curve of best fit returns angular frequency and not period, the error in the period must be calculated from the error in the angular frequency with the following equation:

$$\frac{\delta\omega}{\omega} = \frac{\delta T}{T} \tag{5}$$

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

The X-ray light curve that is obtained from the Chandra database is shown in Figure 5. Three separate observations are plotted on the same plot to present a contiguous set that spans a wide range of time. There is dipping seen in this particular plot, which is possibly due to the heterogeneous stellar wind that impacts the count rate depending on the particular characteristics (mainly temperature) of the gas which crosses our line of sight [3].

Figure 6 shows the count rate vs energy plots of separate observations. Observation 9847 shows the greatest number of X-ray counts with energies being at around 1.6-2.7 keV, corresponding to sulfur and silicon absorption lines [3].

IV.   DISCUSSION

In comparison to accepted publications, our value for the orbital period matches quite well with the literature, with the accepted value being 5.6 days. Our methods for data collection could be improved however, since the calculated magnitudes have relatively high error bars, as seen in 4. To make the curve of best fit more precise, the experiment could be replicated to do many more
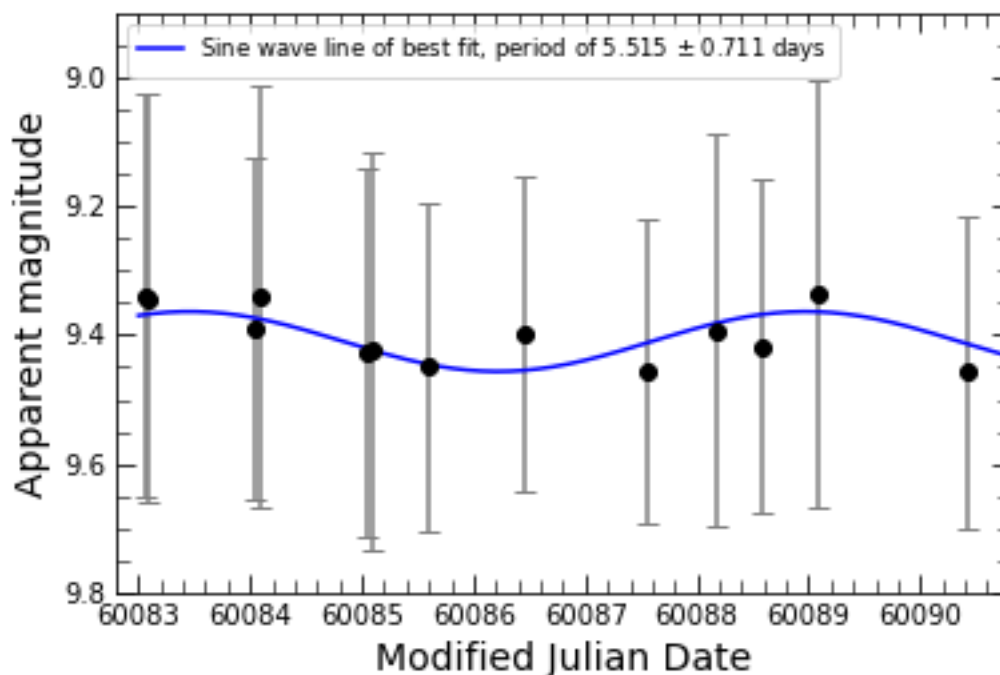
Figure 4: Light curve created using data from the LCO telescope.
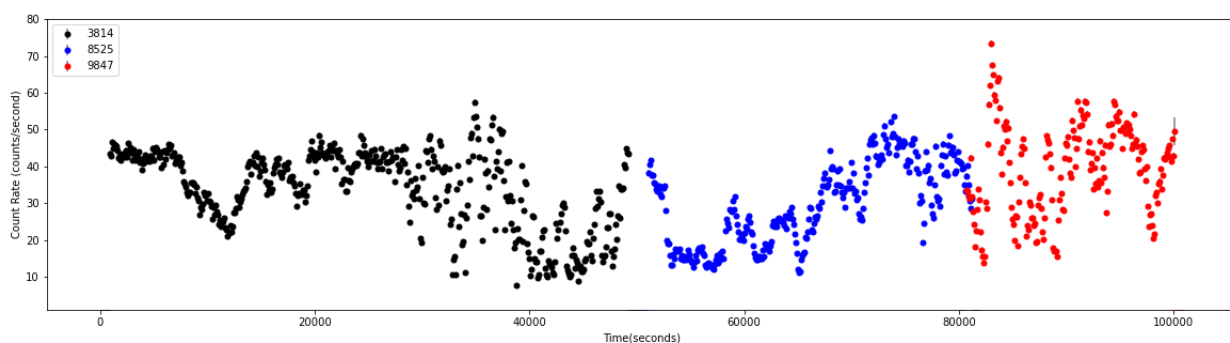

Figure 5: Chandra X-ray data light curve.

observations over a larger time frame.

One source of improvement for our data collection is not using a filter in future experiments. Using a filter brought some limitations since it lowered the values for apparent magnitude and therefore took away from the discrepancy between data points, leading to imprecision. Additionally, sky-map.org did not use the Bessel B-filter in their calculation for apparent magnitude, which caused further discrepancy when comparing our apparent magnitude values to the website's values.

Taking more data points per day with the LCO could have also benefited our data, since we
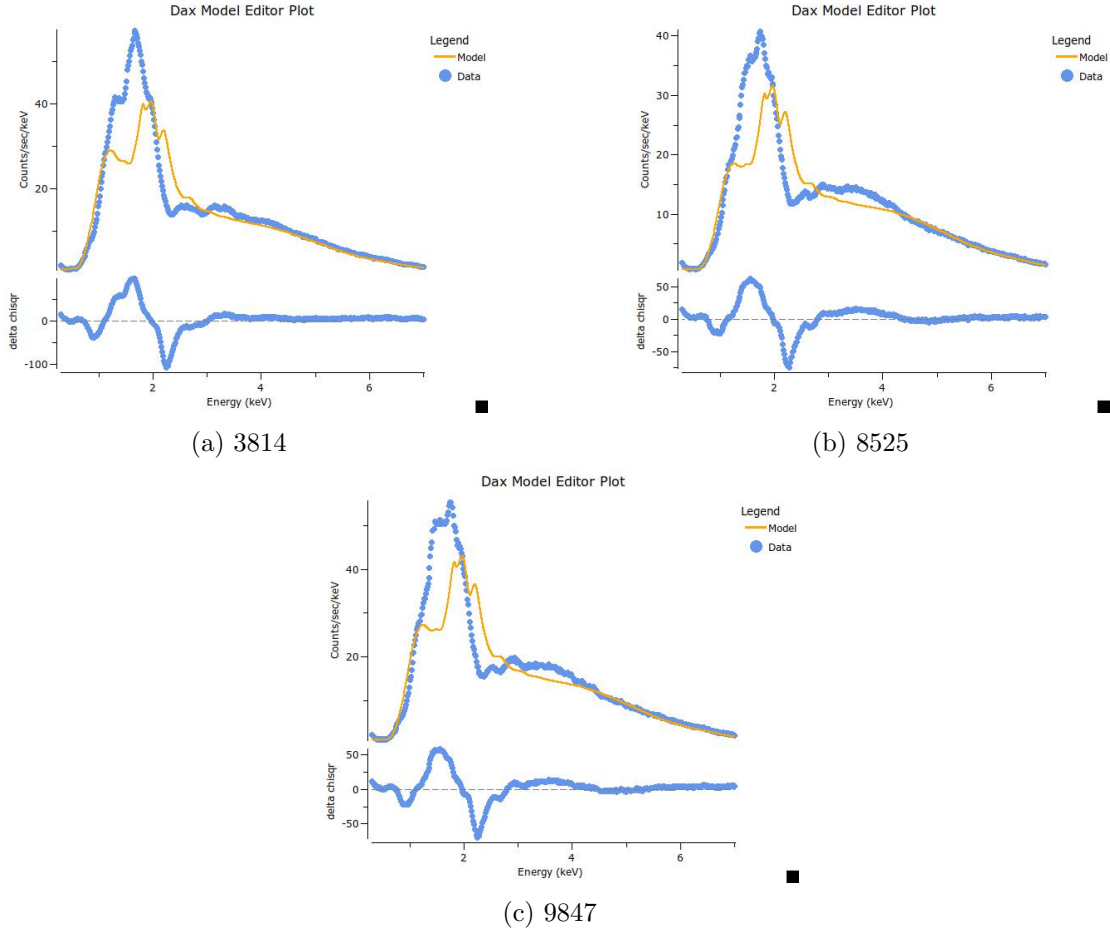
(a) 3814

(b) 8525

(c) 9847

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

would have gotten an average daily magnitude that is made up of a greater number of points, making it less prone to error.

To lower the standard deviation, a higher number of reference stars could have been used. This would have shortened the error bars for each data point on the light curve plot (4). The reason for this is becuase the standard deviation is proportional to $\frac{1}{\sqrt{N}}$ where N is the number of reference stars used.

Lastly, general learning curve of the Chandra archive data was a notable disadvantage for our data analysis. The time consuming procedure, as well as the confusion that came along with using such an expansive and exhaustive dataset did compromise our ability to process and interpret our data.

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[2] J. R. Ducati. VizieR Online Data Catalog: Catalogue of Stellar Photometry in Johnson's 11-color system. *VizieR Online Data Catalog*, January 2002.

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[4] Jerome A. Orosz, Jeffrey E. McClintock, Jason P. Aufdenberg, Ronald A. Remillard, Mark J. Reid, Ramesh Narayan, and Lijun Gou. The mass of the black hole in cygnus x-1. *The Astrophysical Journal*, 742(2):84, nov 2011.