Draft version December 19, 2020
Typeset using LaTeX **preprint2** style in AASTeX63

Measuring the distance to CY Aquarii with RHO

Alyssa Bulatek ,[1] Michael Estrada,[1] Rachel Losacco,[1] and Sheila Sagear[1]

[1]*Department of Astronomy, University of Florida, Gainesville, FL 32611*

ABSTRACT

Variable stars are an important rung in the astronomical distance ladder. The distance to a variable star can be measured by deriving its absolute magnitude based on its pulsation period. CY Aquarii (CY Aqr) is a variable star with a relatively short pulsation period (about 88 minutes). We took 494 usable images of CY Aqr with the telescope at Rosemary Hill Observatory (RHO). We performed aperture photometry on CY Aqr using these images and created a light curve to measure CY Aqr's change in estimated instrumental magnitude over time. Using the light curve, we estimate the pulsation period of CY Aqr (between 69 and 75 minutes) and use this period to determine the expected absolute magnitude of the star (between $M_V = -1.81$ and $M_V = -2.08$). Using the absolute magnitude and the average apparent magnitude in the V band that we estimate (21.6), we derive a distance to CY Aqr of between 4.70×10^5 and 5.32×10^5 pc. This is not close to CY Aqr's distance value from Hipparcos of 1400 pc, which may be explained by a variety of errors in the analysis process.

Keywords: CY Aqr, SX Phoenicis variable stars (1673), multi-periodic variable stars (1079), pulsating variable stars (1307), periodic variable stars (1213), intrinsic variable stars (859), variable stars (1761), stellar types (1634), stellar astronomy (1583)

1. INTRODUCTION

Variable stars have pulsation periods that are related to their absolute magnitude. In order to measure the distance to a variable star, we can measure both its average apparent magnitude and its pulsation period, and use its measured period to determine what its absolute magnitude should be. Then, we can use the distance modulus to determine the distance to the variable star given its absolute and apparent magnitudes. CY Aquarii (CY Aqr) is a well-studied SX Phoenicis variable star (Hardie & Tolbert 1961; McNamara et al. 1996; Wiedemair et al. 2020, eg.). According to the AAVSO entry on the star,[1] CY Aqr has a pulsation period of about 88 minutes and a magnitude range during its pulsation of 10.42 to 11.14 in the V band. This makes CY Aqr a good candidate for observing with limited time on a ground-based telescope, the sensitivity of which might not be sufficient to detect a very small fluctuation in brightness.

Corresponding author: Alyssa Bulatek
abulatek@ufl.edu

[1] https://www.aavso.org/vsx/index.php?view=detail.top&oid=970

In this article, we present the results of photometric observations of CY Aquarii taken during Fall 2020. In Section 2, we describe how our observations were conducted and detail our data reduction process. In Section 3, we discuss how we performed aperture photometry on CY Aqr with our data. We also describe how we create a light curve to show the changing brightness of CY Aqr over time and how we estimate the distance to the star using that light curve. In Section 4, we present our light curves for two nights of observations, make an estimate of the brightness variation of CY Aqr over its period, and estimate the period of CY Aqr's pulsation. In Section 5, we discuss the features of our light curves and discuss sources of error in the data and how to improve them. We conclude in Section 6.

2. OBSERVATIONS

We obtained photometric observations of CY Aqr in the V band using the Rosemary Hill Observatory on three nights: October 26 (into October 27), November 2, and November 3. Throughout this article and the associated code, I refer to each date of observing as "day 1," "day 2," "day 3," and "day 4" for logistical convenience as the dates were included in the image file names, but data from days 1 and 2 were taken sequentially across a single night. A total of 773 images of CY Aqr were taken over those three nights. However, due to irregular movement of the CCD and/or the telescope during guiding, the stars in some images appear obviously distorted. 73 affected images were identified by eye and excluded from the data reduction process before it began. Additionally, due to the CCD being out of focus and causing our photometry function to perform at a subpar level, we did not use the data from days 1 and 2 in our analysis. Our data from that first night did not cover a full pulsation period of the star, so it would not be as easy to incorporate into our cursory analysis of the period.

This left us 553 images to work with in our initial set of images. We used an exposure time of 15 seconds for each image of CY Aqr, which we chose in order to have a sufficient signal-to-noise ratio in detecting CY Aqr while sampling its pulsation period well. Calibration dark and flat frames were taken each night.

2.1. *Data Reduction*

Our data reduction and analysis was written in Python. The Jupyter Notebook used to perform data handling and data analysis is located on my GitHub account.[2] In the data reduction process, we dark-subtracted and flat-field-corrected each science frame using the appropriate calibration frames for each night.

We chose not to align the images automatically, as an algorithm would have a difficult time aligning an image with so few stars in it (depending on the frame, sometimes less than 10 bright stars). Therefore, locating CY Aqr in each image had to be done semi-manually. For each night, a mask with pixel locations where CY Aqr could be located was generated and passed to our photometry function.

3. METHODS

3.1. *Aperture Photometry*

We performed aperture photometry on CY Aqr in each frame in order to measure its instrumental magnitude. We used `photutils.DAOStarFinder` to both locate CY Aqr within our mask in each frame and perform aperture photometry on the star.

Our photometry process begins by calculating 3σ-clipped statistics on a frame to calculate the mean, median, and standard deviation of the pixels in the frame. We then create a `DAOStarFinder` object that will search for the brightest peak above a threshold value (we

[2] https://github.com/abulatek/classes/blob/main/ast6725/photometry_project/ast6725_photometry_project_bulatek.ipynb

used 10σ) with a full width at half maximum (FWHM) near a given value. We chose to use a fixed FWHM value of 6 pixels. We did not provide the finder with a measure of the sky background to subtract this from the star's flux when performing aperture photometry, which could decrease our measured apparent magnitude and, consequently, decrease our measured distance.

Because we did not align our images and searched for CY Aqr within a mask in each frame, each frame was manually checked to ensure that `photutils.DAOStarFinder` did not misidentify a hot pixel or cosmic ray hit as CY Aqr. For each frame, if the peak found was not CY Aqr, that frame was removed from the analysis pipeline manually (this was only the case for four frames from day 3 and one frame from day 4).

Occasionally, `DAOStarFinder` failed to locate CY Aqr within the masked region because its shape was not within the default parameters of the function. This is likely due to those frames being significantly affected by CCD or telescope movement during the exposure. We consider those frames unusable for our analysis and they are not considered further. Finally, we removed 20 frames at the beginning of our day 3 observations, as a large section of frames immediately after those frames were compromised and so the remaining frames did not contribute to the overall shape of the light curve.

After ignoring frames with non-CY Aqr peaks, frames where CY Aqr could not be found, and frames at the beginning of our day 3 observations, we are left with 494 valid instrumental magnitude measurements to work with across days 3 and 4.

3.2. *Magnitude Calibration*

We did not observe standard stars during any night of our observations. This means we do not have stars with which to calibrate our instrumental magnitude measurements of CY Aqr. However, we estimated the zero point of our detector in previous observations (for the photometry homework assignment, for which data were taken on October 17 with the same CCD), so we added this zero point (20.96) to our instrumental magnitudes to estimate the apparent magnitude of CY Aqr over time.

3.3. *Light Curve and Period Estimation*

Using our apparent magnitudes and the time of each observation, we created a light curve to show CY Aqr's brightness variation over time. We estimated the pulsation period using our light curve from day 4 by applying a median filter to the data and measuring the time between the light curve returning to a given median value.

3.4. *Distance Estimation*

We used the following period-luminosity relationship adapted from Equations 4 and 5 in McNamara (1995) to estimate the absolute luminosity of CY Aqr,

$$M_V = -3.29 \log P - 1.35, \qquad (1)$$

where M_V is the absolute magnitude in the V band and P is the pulsation period of the star. We interpret the logarithm as the natural logarithm. Equations 4 and 5 in McNamara (1995) apply to certain classes of SX Phoenicis stars. Since the authors do not know CY Aqr's exact type, we take the average of the offset terms in those equations to get an offset of -1.35. Finally, we used the distance modulus equation to estimate the distance d in parsecs to CY Aqr using our measured apparent magnitude m and estimated absolute magnitude M.

$$\log_{10}(d) = 1 + \frac{m - M}{5} \qquad (2)$$

We compare our estimate to the distance to CY Aqr as measured (in parallax) by Hipparcos from the VizieR catalog[3] for the mission, as Gaia DR2 has several sources within a 2 arcminute radius of CY Aqr.

4. RESULTS

4.1. *Light Curves*

We created light curves of the apparent magnitude of CY Aqr over time for day 3 and day 4. Our light curve for day 3 is shown in Figure 1, and our light curve for day 4 is shown in Figure 2. We also applied a median filter of size 25 to each light curve to reduce noise in order to estimate the period more easily; the median-filtered light curves are shown in each respective figure alongside their non-filtered counterparts. The 25-point filter means that at each point along the light curve, that point is replaced by the median of the 25 points surrounding it (itself and 12 points on either side). At the beginning and the end of the light curve, edge effects occur, as the number of data points to one side are limited, so these median values will not be as reflective of the data at those times.

Our light curve for day 3 spans slightly less than one expected period of CY Aqr (about 88 minutes). It seems to be affected by a steep increase in brightness at around 40 minutes from the start of the time series. Therefore, we will not use our day 3 light curve to estimate the period or the magnitude variation of CY Aqr. Qualitatively, we can see an increase in brightness at either end of the light curve, suggesting we can recover some of the variation in brightness we expect.

Our light curve for day 4 looks closer to what we would expect from a variable star's light curve. Qualitatively, we see a slow dip in brightness halfway through the night, then a steeper increase in brightness before reaching the peak value and slowly decreasing again. There is more scatter in the brightness of CY Aqr during its slow dimming than its quick brightening, but this is likely an effect of the different amount of time each of those processes takes.

[3] https://vizier.u-strasbg.fr/viz-bin/VizieR?-source=1239/hip_main

4.2. *Brightness Variation Estimate*

We can make a rough estimate of the variation in brightness of CY Aqr by measuring the mean value near the dimmest part of the light curve and subtracting that brightness from the mean value at the brightest part of the light curve. We estimate a difference of about 1.5 (as this is an estimate and not a science goal of this paper, we will not propagate uncertainties on this value). The AAVSO entry for CY Aqr lists the star as varying between 10.42 to 11.14 magnitudes in the V band (0.72), which is relatively close to our estimate.

4.3. *Period Estimation*

We estimate the period using the median-filtered day 4 light curve. We choose our first median value away from the beginning of the light curve because of the edge effects of the median filter. The first median we chose is 29 timesteps into the series (just over 10 minutes into the observation), which is shown as the solid red vertical line in Figure 2. We estimate by eye where the median (the horizontal solid blue line) returns to that value after the brightness of CY Aqr peaks. This could occur over a range of times (denoted by the green region bounded by dashed green lines), from about 80 to 85 minutes into the observation. Using our exact timesteps, we estimate the period of CY Aqr to be somewhere between 69 minutes and 75 minutes using this method.

We can plug this range of periods (in units of decimal hours) into Equation 1 to estimate a range of absolute magnitudes these periods correspond to. This yields a range of absolute magnitudes from $M_V = -1.81$ to $M_V = -2.08$. We estimate an average apparent magnitude across our unfiltered day 4 light curve of 21.6. Using the distance modulus (Equation 2), these absolute magnitudes correspond to a distance range of 4.70×10^5 pc to 5.32×10^5 pc.

5. DISCUSSION

There are many problems with this analysis that lead to results which don't match those in the literature. The first problem comes from our methods for aperture photometry. Changing the FWHM value used for measuring the magnitude of CY Aqr affects the shape and overall level of the light curve greatly (Sheila Sagear, personal correspondence). Therefore, using a fixed pixel-based FWHM is likely not the best method for analyzing these data. Measuring the PSF in each frame would likely capture the brightness variation of CY Aqr more accurately and bring the light curves derived for different nights to the same overall level. This would be made more simple if there were more stars in our field of view to measure.

The anomalous bump in our day 3 light curve could be caused by this poor method of photometry. It is possible that during the middle 60 minutes of our day 3 observations, the guiding could have been behaving much better than the rest of the night, causing the star's PSF to appear smaller on the detector, allowing us to collect more light from the star within the smaller area. A cursory glance at the images during this time do not reveal any obvious differences between these images and the ones earlier or later in the night, so this may not be the case. The humidity was quite high during all of our observations, so this could have played a role in the quality of our light curves as well.

Not measuring standard stars was also detrimental to our apparent magnitude calculations. This made it so that we were dependent on a previous magnitude calibration, which may not have been accurate for these observations. Though this issue cannot be separated from the magnitude errors induced by a constant pixel-based PSF, it is possible that our apparent magnitudes would have been closer to the literature values if we had calibrated them using standard stars.

The pulsation period range we estimate (between 69 and 75 minutes) does not contain the AAVSO catalog value of around 88 minutes. This could be due to the FWHM we used, as this can change the shape of the light curve and the scatter in it. However, we do see a periodic pulsation, at least in the data for day 4.

The Hipparcos entry for CY Aqr (HIP 111719) gives a trigonometric parallax measurement of 0.71 mas, which corresponds to 1400 pc using the $d = 1/p$ equation. This is nowhere near our estimate of between 4.70×10^5 and 5.32×10^5 pc. However, using the accepted literature values of $m = 10.78$ and $P = 88$ minutes yields a distance of 4800 pc, which also is not close to the Hipparcos value (though it is within an order of magnitude). This leads us to believe that the exact period-luminosity relation we use may not be appropriate for CY Aqr, although it may be appropriate for other short-period SX Phoenicis stars.

A better method of estimating the period of CY Aqr from a light curve would be to fold the light curve at a variety of periods and see which periods result in a light curve with the strongest signal. This would ideally involve using multiple nights of data that could be strung together.

6. CONCLUSIONS

We were able to roughly estimate the period of the SX Phoenicis variable star CY Aqr using photometric measurements of a single night of observing. Much of our data was not usable because of CY Aqr appearing extended or as multiple peaks in images, which may be due to poor guiding or tracking. Our third night of data ("day 4") provided us with 250 images of CY Aqr, which we used to perform aperture photometry on CY Aqr. We made an educated guess of the period of CY Aqr using our light curve (between 69 and 75 minutes) and used a period-luminosity relationship for SX Phoenicis variables to translate our estimated period to an absolute magnitude (between $M_V = 1.81$ and $M_V = -2.08$). We then measured the average apparent magnitude from our day 4 light curve, and used the distance modulus to measure a distance to CY Aqr (between 4.70×10^5 and 5.32×10^5 pc).

None of these values are close to the literature values we consult for CY Aqr (we use a period of 88 minutes from AAVSO and a distance of 1400 pc from Hipparcos). This is likely because of a plethora of errors in the analysis process. To name a few, we used a fixed FWHM for aperture photometry, a zero point correction from a previous night of observing (because we did not observe standard stars), and we used a period-luminosity relationship that may not be optimized for our object.

Future work on this project would include observing CY Aqr for a longer period of time to capture more pulsation periods and better measure the period by folding the light curve. We would also benefit from observing standard stars to get an accurate apparent magnitude calibration, and from measuring the FWHM in each image while performing aperture photometry. Despite these errors, the lead author is pretty pleased with the fact that she was able to recreate a periodic light curve with a period that is on the same order of magnitude as the literature value for the source.

ACKNOWLEDGMENTS

The authors wish to thank Sarik Jeram for acquiring the data for this project and for providing useful feedback along the way. AB made use of the QLFits application written by Cédric Foellmi during the data reduction process. This work made use of SAOImageDS9 (Joye & Mandel 2003).

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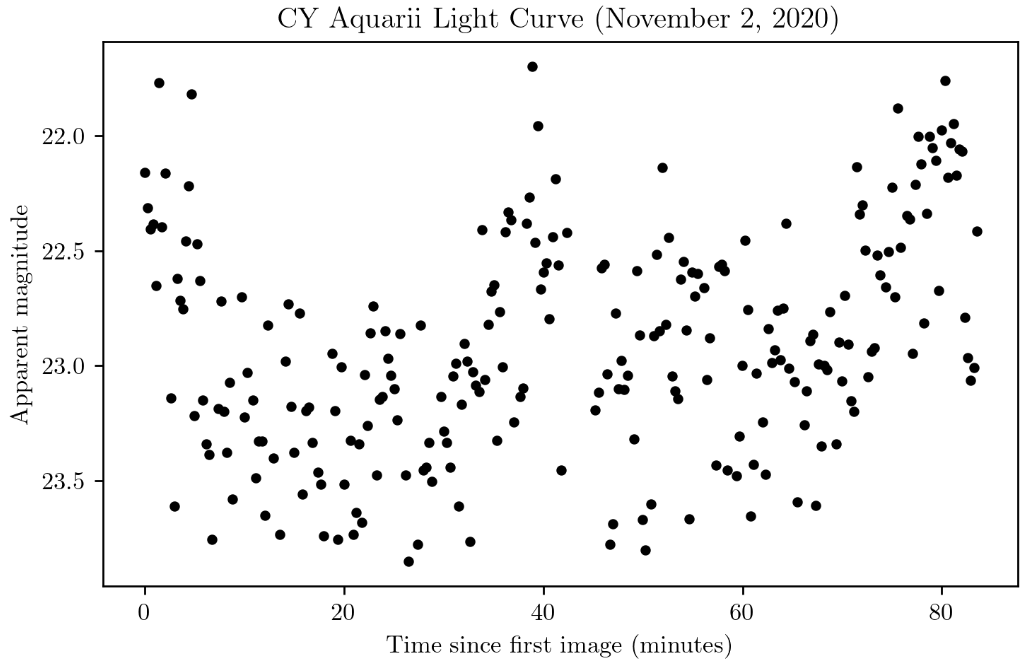

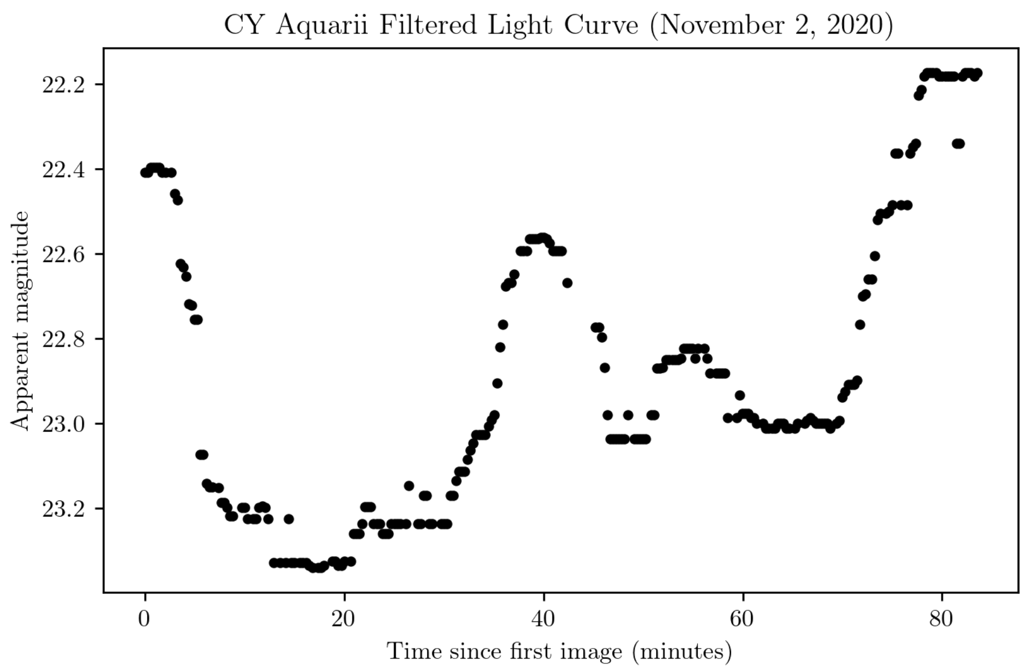

Figure 1. Light curves from our observations of CY Aquarii on November 2, 2020. *Above:* unfiltered light curve with values derived from performing aperture photometry on 244 images of CY Aqr on November 2. There is an increase in brightness in the middle of the expected period of the variable star. We can see an increase in brightness at the beginning and end of the observation. *Below:* median-filtered (25 point width) light curve of CY Aqr on November 2. The median filtering reveals a series of anomalous bumps at around 40 and 60 minutes into the time series. These bumps are not likely to be related to the stellar pulsation, and their sharpness is likely due to the median filtering.

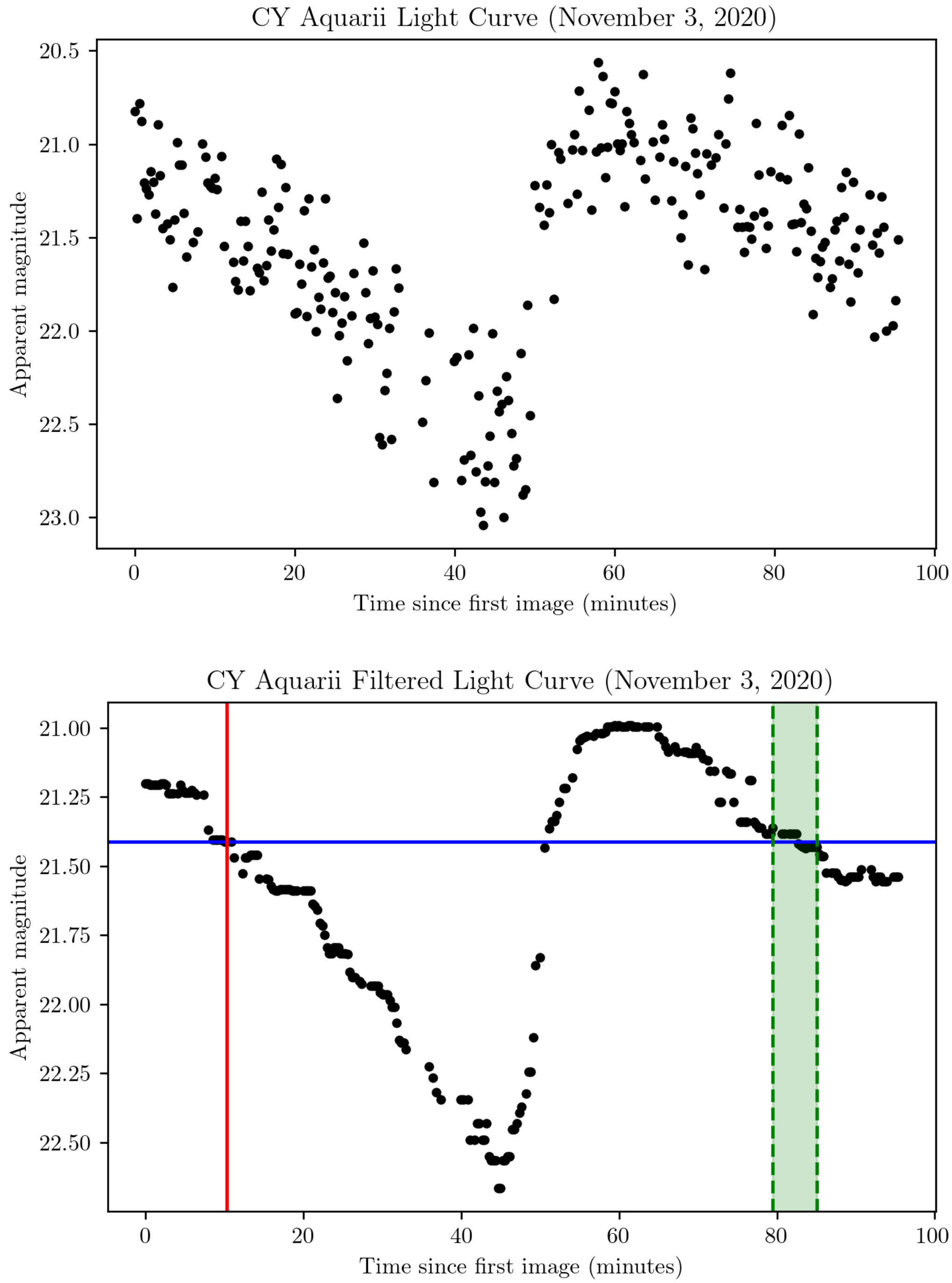

Figure 2. Light curves from our observations of CY Aquarii on November 3, 2020. *Above:* unfiltered light curve with values derived from performing aperture photometry on 250 images of CY Aqr on November 3. A periodicity is apparent at first glance. The spread in apparent magnitude is greater during CY Aqr's slow dimming and less during the quick brightening, but this could be due to there being less data points in that region. *Below:* median-filtered (25 point width) light curve of CY Aqr on November 3. The median filtering smooths out the spread in apparent magnitude during the first half of the light curve. The vertical solid red line shows the first timestep we used to estimate the period, with the corresponding median apparent magnitude value shown as the horizontal solid blue line. A possible range of timesteps (estimated by eye) where the brightness of CY Aqr returns to that median value is shown in the green region, bounded by dashed green lines.