Light Curve of CY Aquarii

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Abstract

CY Aquarii, or HIP111719, is a variable star of the SX Phoenicis class observed by the author's group. The author's group made observations in the Visual band, and determined using differential photometry that the period of the star's brightness oscillation is approximately **87 minutes and 36 seconds**, and that the amplitude of the oscillation is approximately **0.48 mag**. Measurements made by another group in the Blue band yielded a period of 89 minutes and 17 seconds and an amplitude of 0.878 mag. Recent literature yields a period of 87 minutes and 54 seconds and an amplitude of 0.71 mag in V. It will be argued that the amplitude measurement made by the author's group is likely erroneous due to cloudy conditions during their observations.

1 Introduction

The following table summarizes some key information which the reader may want to know about CY Aquarii [SIM]:

Property	Value
Class	SX Phoencis
Right Ascension	22 37 47.852
Declination	+01 32 03.802
Parallax	2.3368 mas
Spectral Type	B8
Peak Magnitude (B)	10.61
Peak Magnitude (V)	10.44

Historical data has suggested that CY Aquarii and other SX Phonencis stars have a short period and high amplitude of variability. CY Aquarii is thus an ideal target for the author's group, since they have limited telescope time and are observing from a location with poor seeing.

2 Experimental Procedure

The goal of this project was to measure the light curve of CY Aquarii and, in particular, its period and amplitude. The author's group's measurements utilized the CCD camera at the 0.8m Krizmanich Telescope at the Jordan Observatory at Notre Dame. Prior to making observations of CY Aquarii, they took 20 flat frames, 10 dark frames, and 70 bias frames. The author's group intended to take the flat frames just after sunset, but ultimately most flat frames were taken when the sky was darker than they would have preferred, making them suboptimal. The author's group chose to make their observations in the Visual band, since CY Aquarii is known to be brightest in the Blue and Visual bands among those filters available at the Krizmanich telescope, and their collaborators Boyle and Sadagopan had already made observations of CY Aquarii in the Blue band (a comparison is forthcoming in the Section 3.2). All images (science, dark, flat, and bias) were taken with 1×1 binning.

The author's group's 80 science frames had an exposure time of 90 seconds. This exposure length was optimized to obtain a strong signal to noise ratio without reaching a nonlinear part of the CCD. This optimization was performed by trial and error, with different exposure times tested, and then the maximum pixel values for the exposure times compared against known measurements for where the Krizmanich's CCD becomes nonlinear. The author's group also made qualitative measurements of the level of saturation by observing images with different exposure times and looking for signs of saturation in bright stars. The author's group's observing log noted that the quantitative and qualitative measurements were in reasonable agreement with one another, and thus the author is reasonably confident that the images have an exposure time which yields a strong signal to noise ratio without introducing nonlinearity in measurements.

2.1 Calibration

Following the conclusion of their observations, the science images that the author's group obtained were calibrated using MaximDL. In particular, the additive effects were removed by subtracting the mean of the dark images. The dark images did not appear to have significant outliers (see Section 4.2, point 4), so the mean is likely an accurate representation of the dark current. Since the dark images had the same exposure time as the science images, it was not necessary to use the bias images during the removal of additive effects from the science images. Multiplicative effects were removed by dividing the image by the median of the flats. The median was used as opposed to the mean since some flats taken were observed to be outliers qualitatively and quantitatively (see Section 4.2, Point 3). As aforementioned, the author's group believes this is a consequence of the flats being taken later in the evening than originally planned. Additive effects were removed from the flats by using both the dark images and bias images, since the exposure time on the flats was considerably shorter than the exposure time on the science images and dark images. The mean image was used for both the dark images and bias images. Once additive effects had been removed from the median flat image, the science images with additive effects removed was divided by the calibrated flat image with additive effects removed, in order to produce a final calibrated science image. This process was conducted for all of the 80 science images taken.

In summary, the following image provides a visual representation of the calibration process:

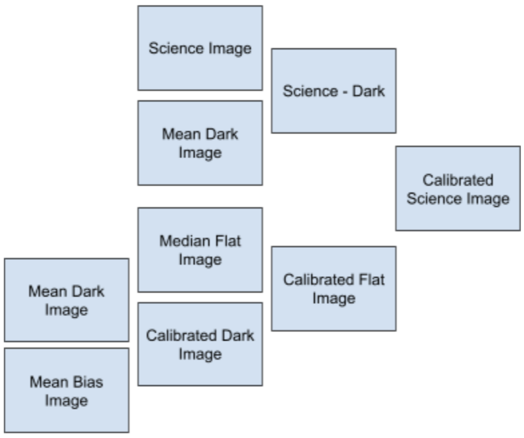

Figure 1: Summary of Calibration Process

2.2 Photometry

To create a light curve for CY Aquarii, the author's group utilized differential photometry in MaximDL. In particular, the author's group specified CY Aquarii as the target object, specified the second, third, and fourth brightest stars as reference stars, and the fifth brightest star as a check star. Using aperture photometry with circular apertures, MaximDL then produced a table of the magnitude of CY Aquarii relative to the reference stars as a function of time.

The primary reason for making differential measurements is that the observing conditions varied across different science images; in particular, the author's group's observing log notes that clouds passed over the observatory while they were observing. Since the reference stars chosen are believed to be non-variable, if the assumption is made that the clouds or other variations in observing conditions had identical[1] impacts on the flux of the reference stars and the flux of CY Aquarii, then the difference between their magnitudes should remain constant[2]. The validity of this assumption will be discussed in Section 4.2, Point 2 and Section 4.3.

3 Results

3.1 Visual Band

The following graph displays the photometry measurements described in Section 2.2:

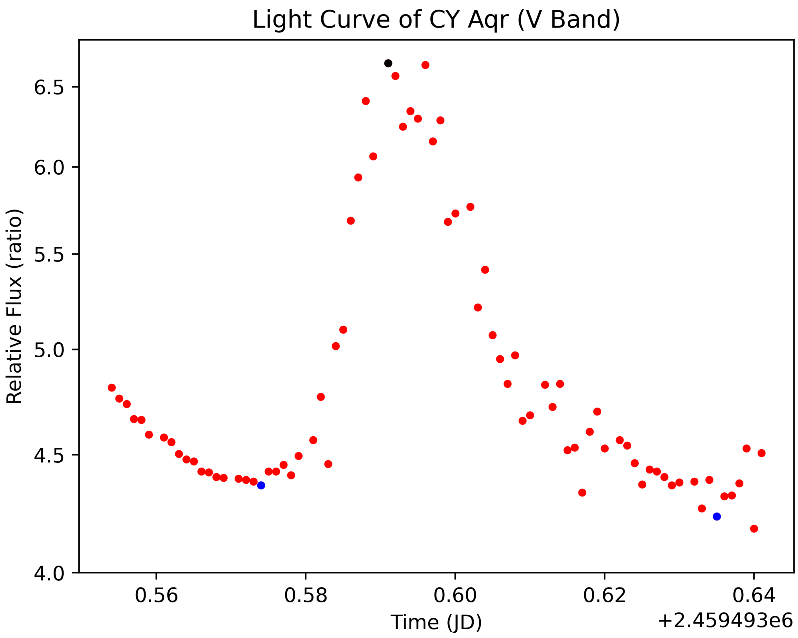

Figure 2: Relative flux of CY Aquarii over Time. The y-axis has been log scaled. Minima used for period calculation are in blue. The maximum used for the magnitude change calculation is in black. Data can be found in tabular form in Appendix 1.

It is worth noting that since the y-axis is scaled logarithmically, the shape of the curve is identical to what it would have been should relative magnitude have been plotted instead of relative flux. The author chose to use relative flux so that the physical meaning of a minimum or maximum on the graph is more intuitive (minimum=less bright, maximum=more bright).

From the minima marked in blue, it was determined that the period of variation is approximately 87 minutes and 36 seconds (calculation in Section 4.1). The difference in magnitude between the earlier minimum and the maximum (marked in black) is 0.46, and the difference in magnitude between the later minimum and the maximum is 0.49. The reader should note that the value for relative flux is not the same at the two minima; this will be discussed further in Section 4.

3.2 Blue Band

The following graph displays similar measurements made in the Blue band by Boyle and Sadagopan:

[1] Identical here meaning that they increase/decrease their flux by the same ratio (*not* by the same amount of flux in absolute terms)

[2] Utilizing the relation $(m_2 - m_1) \propto \log\left(\frac{F_2}{F_1}\right)$.

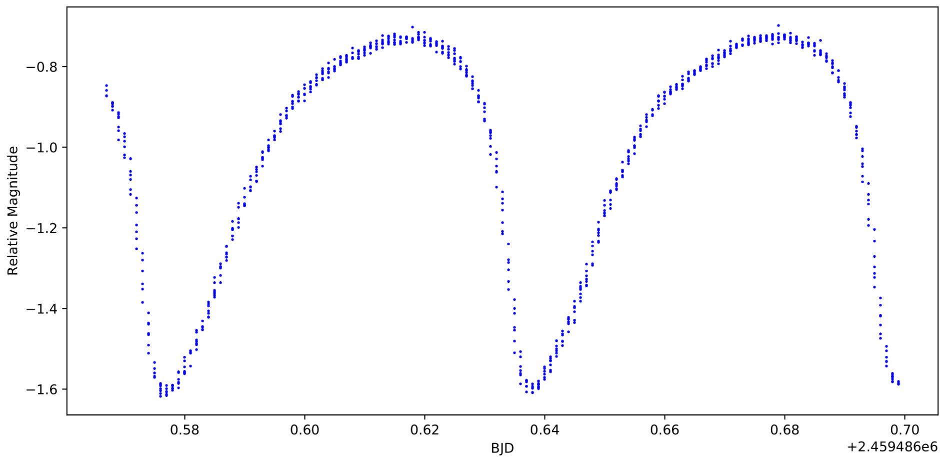

Figure 3: Relative magnitude of CY Aquarii over Time. Data can be found in tabular form in Appendix 2.

A few comments are necessary. First, a far larger number of data points were obtained, both due to a longer length of observation and a smaller exposure time. Second, the y-axis of Figure 3 is inverted relative to the y-axis of Figure 2. Whereas a peak on Figure 2 indicates a relative maximum in the flux of CY Aquarii, a peak on Figure 3 indicates a relative minimum in the flux of CY Aquarii. Third, the observing conditions during these observations were far better than the observing conditions during the observations in the Section 3.1. This is apparent both from the data itself and from the respective observing logs.

With that said, the reader can observe that if outliers within Figure 2 are ignored, then the shape of the curve depicted in Figure 2 is generally consistent with the shape of the curve depicted in Figure 3.

From these measurements, it was determined that the period of oscillation is 89 minutes and 17 seconds and the amplitude of oscillation is 0.878 mag in B [Palb].

3.3 Literature

A comparison to literature here is restricted to Wiedemair et al., who have conducted extensive CCD photometry on CY Aquarii from 2012 to 2020 [Wie+20] [Wie+18] [Wie+16]. Their publications indicate that the period of oscillation for CY Aquarii is 87 minutes and 54 seconds, and the amplitude of oscillation for CY Aquarii is 0.71 mag in V.

4 Discussion

4.1 Calculation of Period

Given that the light curve (Figure 2) appears visually to capture two minima but only one maximum, the period was calculated by finding the difference in time between the two minima. Among values prior to the peak, the minimum is rather obvious; however, among later values, there is much more noise and the minimum is much less obvious. The latter point in blue was chosen visually based upon the graph of the light curve; it appeared to be the point which marks the minimum before the curve begins to increase at the very end of the curve. It was determined that a visual analysis of the graph was a more reliable method than mathematical analysis due to the noise in the light curve in that region. From the times of the two minima, the period was measured to be 87 minutes and 36 seconds, as mentioned in Section 3.1. This period was calculated by subtracting the time of the earlier minimum from the time of the later minimum.

4.2 Sources of Error

1. The Poisson error ($\sqrt{N}$) is unavoidable independent of experimental procedure. However, this does not appear to be a major source of error in the photometry measurements.

2. Return to the aforementioned assumption that changes in observing conditions would have identical impacts on the magnitudes of CY Aquarii and its reference stars (Section 2.2). This does not appear to be a legitimate assumption based upon the data. Recall that the author's group noted in their observing log that observing conditions were worse towards the end of their observations relative to the conditions towards the beginning of their observations. We see in Figure 2 that there is a considerably larger amount of noise in the measurements towards the end of the observations than at the beginning of the observations. Whereas Section 2.2 described the assumption that the author made that the magnitudes of CY Aquarii and the reference stars would change identically (hence maintaining the same relative magnitude), this assumption appears to be invalid based upon the data. Hence a considerable amount of error is introduced by the poor observing conditions towards the end of the observations.

3. Return to the remark in Section 2 regarding the quality of the flat frames. It was remarked earlier that the flat frames had a considerable amount of variation, and it was suggested that this was due to the flat frames being taken too late after dusk such that the sky was no longer uniform in the region in which the telescope was pointed. That there is a considerable amount of variation is confirmed by a statistical analysis on the flat images taken. In particular, for each pixel, the ratio of the median absolute deviation of the values of that particular pixel across the flat images to the median of the values of that particular pixel was calculated [Pala]. Written mathematically, for some pixel (i, j), say $m = \text{median}\{\text{image}[i, j] : \text{image} \in \text{flat images}\}$. Then the calculated value for that pixel is
$$\frac{\text{median}\{|\text{image}[i, j] - m| : \text{image} \in \text{flat images}\}}{m}$$
It was measured that the mean of this calculated value across all 1048576 pixels was **35.9%**. This indicates a very significant variation in the flat images taken. Since the flat images were taken in close proximity to one another (both temporally and spatially), this indicates that the region of sky which the flats were taken over was likely not a very uniform region, making the flats fairly unreliable. Hence the calibration described in Section 2.1 is unreliable with respect to multiplicative effects.

4. Since the reliability of the flats has been discussed, it is fitting to discuss the reliability of the darks and biases as well. For these, since a mean was used rather than a median, the ratio calculated for each pixel was the ratio of the standard deviation (rather than median absolute deviation) to the mean. In the case of the darks, the mean of this calculated value across all pixels was 0.646%, and in the case of the biases, the mean of this calculated value across all pixels was 0.603%. This indicates that the darks and biases are very consistent, as would be expected given that they were taken back to back and the dark current and bias in a CCD device does not change very quickly over time. Thus the calibration described in Section 2.1 is reliable with respect to additive effects.

4.3 Discrepancy in Amplitude

From Section 3, the reader can see the fact that while there is reasonable agreement between the Visual band measurements, Blue band measurements, and literature values on the period of oscillation, there is considerable disagreement on the amplitude of oscillation. Specifically, the amplitude measured by the author's group was significantly smaller than the amplitude measured by Boyle and Sadagopan (in the Blue band), and the literature value cited (which was measured for V). Certainly, a discrepancy would be expected between the amplitude measured for B and the amplitude measured for V, but one would expect a smaller discrepancy between the measurement in V and the literature value also in V. This is likely attributable to the observing conditions on the night that the observations depicted in Figure 2 were conducted.

The observing log records clouds passing over in the middle of observations. Thus, it is probably the case that during the brightest part of CY Aquarii's light cycle, the flux of CY Aquarii was dimmed by the cloudiness. From Figure 2, the reader can see that the minimum value for CY Aquarii's relative flux observed towards the end of the observations was smaller than the minimum value observed towards the beginning of the observations. This suggests that the clouds were causing a greater decrease[3] in flux for CY Aquarii than for the reference stars[4]. Accordingly, the

[3] Not only in absolute terms, but also in terms of a percentage change.

[4] Note that this observation also corroborates the comments made in Section 4.2, point 2.

amplitude would appear to be smaller since the maximum flux would be smaller than it would have been in the initial observing conditions from that night.

This explanation is undermined by the fact that the discrepancy between the magnitudes of the two minima was only 0.03 mag, while the discrepancy between the literature value for amplitude and the measured value for magnitude was 0.23 mag. Certainly, the explanation is not foolproof and further investigation would be required to confirm that the discrepancy is not the result of instrument error, procedural error, etc. in either the measurements presented in this paper or (much less likely) the measurements which led to the literature value. However, the observing log recalls that the clouds were most potent during the middle of the observations and accordingly were less potent at the end of the observations. This indicates that it is reasonable to infer that if the clouds were the source of the discrepancy, they would cause a greater discrepancy between the measured maximum and what the measured maximum would have been without the clouds than the discrepancy between the two minima.

This explanation is also corroborated by the strong agreement between the measured periods described in Sections 3.1, 3.2, and 3.3. If the source of error in the measurements had been the result of significant instrument error or procedural error, then it is likely that significant error would have been introduced into the period measurement (i.e. the locations of the relative minima). On the other hand, clouds do not introduce a significant amount of error into the locations of the relative minima, since they have a very similar impact on points within a small neighborhood of each other, and thus do not have a major impact on the measurement of relative minima, since these are found on a local basis. Hence the fact that the period measurement appears reliable corroborates the explanation that the discrepancy in the amplitude measurement is due to the clouds.

5 Conclusion

Based on the photometric analysis performed on CY Aquarii, it was measured that the period of oscillation is 87 minutes and 36 seconds, and that the amplitude of oscillation is approximately 0.48 mag. The period measurement is believed to be fairly reliable, but the amplitude measurement is believed to be unreliable due to cloudiness on the night observations were conducted. Further investigation is needed to confirm this hypothesis.

Acknowledgements

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Appendix - Table of Relative Magnitude Measurements

The data plotted in Figure 2 consists of the leftmost two columns. Notice that the relative magnitude of the reference stars are not zero. This is because multiple reference stars were used.

Julian Date	CY Aqr (mag)	Ref1 (mag)	Ref2 (mag)	Ref 3 (mag)	Check (mag)
2459493.554	-1.706	-0.972	1.245	1.572	1.342
2459493.555	-1.694	-0.973	1.241	1.591	1.349
2459493.556	-1.688	-0.968	1.228	1.557	1.304
2459493.557	-1.672	-0.962	1.185	1.557	1.328
2459493.558	-1.671	-0.968	1.225	1.561	1.412
2459493.559	-1.655	-0.965	1.256	1.492	1.401
2459493.561	-1.652	-0.967	1.233	1.542	1.369
2459493.562	-1.647	-0.971	1.248	1.558	1.42
2459493.563	-1.634	-0.97	1.226	1.583	1.416
2459493.564	-1.628	-0.965	1.229	1.523	1.349
2459493.565	-1.626	-0.97	1.239	1.56	1.303
2459493.566	-1.615	-0.964	1.235	1.509	1.374
2459493.567	-1.614	-0.967	1.219	1.56	1.33
2459493.568	-1.609	-0.966	1.212	1.555	1.356
2459493.569	-1.608	-0.974	1.262	1.572	1.346
2459493.571	-1.607	-0.972	1.246	1.578	1.373
2459493.572	-1.606	-0.966	1.226	1.537	1.36
2459493.573	-1.604	-0.968	1.212	1.584	1.394
2459493.574	-1.6	-0.964	1.227	1.519	1.406
2459493.575	-1.615	-0.965	1.204	1.556	1.38
2459493.576	-1.615	-0.972	1.247	1.572	1.353
2459493.577	-1.622	-0.972	1.247	1.57	1.365
2459493.578	-1.611	-0.973	1.253	1.574	1.357
2459493.579	-1.632	-0.971	1.253	1.555	1.385
2459493.581	-1.649	-0.972	1.25	1.57	1.322
2459493.582	-1.696	-0.971	1.232	1.585	1.353
2459493.583	-1.623	-0.972	1.261	1.557	1.379
2459493.584	-1.751	-0.97	1.245	1.555	1.392
2459493.585	-1.769	-0.972	1.238	1.585	1.37
2459493.586	-1.887	-0.973	1.24	1.592	1.396
2459493.587	-1.934	-0.966	1.237	1.524	1.391
2459493.588	-2.017	-0.972	1.252	1.566	1.387
2459493.589	-1.957	-0.971	1.257	1.551	1.337
2459493.591	-2.058	-0.97	1.245	1.552	1.339
2459493.592	-2.044	-0.97	1.258	1.542	1.336
2459493.593	-1.989	-0.967	1.25	1.522	1.298
2459493.594	-2.006	-0.966	1.232	1.528	1.314
2459493.595	-1.998	-0.943	1.283	1.269	1.351
2459493.596	-2.056	-0.968	1.245	1.531	1.339
2459493.597	-1.973	-0.967	1.252	1.511	1.342
2459493.598	-1.996	-0.967	1.253	1.516	1.341
2459493.599	-1.886	-0.966	1.246	1.516	1.339
2459493.6	-1.895	-0.973	1.281	1.541	1.389
2459493.602	-1.902	-0.965	1.235	1.523	1.383
2459493.603	-1.793	-0.955	1.264	1.39	1.426
2459493.604	-1.834	-0.949	1.269	1.336	1.395
2459493.605	-1.763	-0.956	1.281	1.384	1.393
2459493.606	-1.737	-0.953	1.258	1.382	1.388
2459493.607	-1.71	-0.958	1.301	1.375	1.395
2459493.608	-1.741	-0.952	1.271	1.36	1.387
2459493.609	-1.67	-0.954	1.27	1.377	1.387
2459493.61	-1.676	-0.956	1.282	1.375	1.415

2459493.612	-1.709	-0.974	1.244	1.599	1.377
2459493.613	-1.685	-0.971	1.253	1.555	1.352
2459493.614	-1.71	-0.972	1.269	1.542	1.356
2459493.615	-1.638	-0.945	1.261	1.31	1.375
2459493.616	-1.641	-0.95	1.271	1.338	1.378
2459493.617	-1.592	-0.949	1.265	1.337	1.388
2459493.618	-1.658	-0.954	1.283	1.357	1.367
2459493.619	-1.68	-0.977	1.281	1.58	1.343
2459493.62	-1.64	-0.973	1.273	1.545	1.338
2459493.622	-1.649	-0.97	1.239	1.566	1.335
2459493.623	-1.643	-0.972	1.256	1.561	1.374
2459493.624	-1.624	-0.973	1.262	1.561	1.355
2459493.625	-1.601	-0.971	1.234	1.577	1.373
2459493.626	-1.617	-0.97	1.234	1.567	1.392
2459493.627	-1.615	-0.972	1.252	1.565	1.363
2459493.628	-1.609	-0.972	1.242	1.581	1.374
2459493.629	-1.6	-0.968	1.245	1.533	1.385
2459493.63	-1.603	-0.974	1.27	1.56	1.314
2459493.632	-1.604	-0.973	1.274	1.544	1.311
2459493.633	-1.575	-0.97	1.249	1.552	1.321
2459493.634	-1.606	-0.974	1.241	1.602	1.321
2459493.635	-1.566	-0.973	1.264	1.56	1.325
2459493.636	-1.588	-0.975	1.275	1.566	1.317
2459493.637	-1.589	-0.974	1.266	1.57	1.302
2459493.638	-1.602	-0.973	1.256	1.571	1.35
2459493.639	-1.64	-0.97	1.241	1.557	1.306
2459493.64	-1.553	-0.967	1.245	1.528	1.301
2459493.641	-1.635	-0.972	1.233	1.594	1.328