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RRc Lyrae Star SS Psc's Light Curve along with its photometric properties

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ABSTRACT

RR Lyrae stars are important to astronomy because of their acting role as standard candles. These stars have oscillations in their apparent magnitude that can be measured through the use of CCD cameras. Through these CCD images, one can obtain the apparent magnitude light curve and the period of the star. Using these two values, the metallicity, [Fe/H] abundance, and distance from the star can be found. In this paper, we specifically look at RRc Lyrae star SS Psc, which was observed on nights October 28, 2019, November 4, 2019, and November 6, 2019. We measured a period of 0.325 days $\pm$ 0.00621 days, which has a significance level of 0.36σ compared to Ferro et al. (2012)'s value of 0.288 days $\pm$ 0.100 days and a significance level of 0.38σ compared to Pena et al. (2008)'s value 0.287 days $\pm$ 0.100 days. The metallicity measured was -1.36 $\pm$ 0.172, which has a significance level of 1.7σ compared to Ferro et al. (2012)'s value of 0.88 $\pm$ 0.21, and a significance level of 5.8σ compared to Pena et al. (2008)'s value of -0.2 $\pm$ 0.1. Lastly, the distance from the star was measured at 999.75 pc $\pm$ 103.99 pc, where has a significance level of 0.35σ compared to Marsakov et al. (2018)'s value of 959 pc $\pm$ 50 pc. All of our measurements were consistent with values from literature besides the metallicity's measurement compared to Pena et al. (2008)'s value.

1. INTRODUCTION

Some of the most important objects in the universe are standard candles. Standard candles are astronomical objects that have a known absolute magnitude. Examples of standard candles are RR Lyrae stars, Cepheid Variable stars, and Type Ia supernovae. The distance modulus equation is

$$M = m - 5log_{10}\left(\frac{d_L}{10pc}\right), \tag{1}$$

where M is the known absolute magnitude, m is the apparent magnitude, and d_L is the luminosity distance to the light source in parsecs (Ryden 2017). Since observers can measure the apparent magnitude of the standard candle, one can measure the distance away from the object using the measured apparent magnitude and the inferred absolute magnitude.

This paper will focus on RR Lyrae stars, specifically the RRc Lyrae star SS Psc. One of the important qualities of this star is that its' apparent magnitude acts almost like a sinusoidal wave. Due to its relatively short period, its full period could be observed in one day. SS Psc also has a bright magnitude, so it would be easily observable at our location. These are the reasons why SS Psc was chosen.

Due to weather constraints, SS Psc was observed on three nights. These three nights were October 28, 2019, November 4, 2019, and November 6, 2019. The telescope that was used to observe them was the 14-inch Meade LX200-ACF telescope on a Mesu-200 German Equatorial Mount (Meade 2019). To measure the apparent magnitude, which was in the visual band, of SS Psc, we had to take CCD images of the star on each night. The Charged-Coupled Device (CCD) camera that was used in this experiment was the SBIG STL-1001E CCD (CCD 2019). Using these science images and many data reduction steps, the period, metallicity, and distance to the star can be found. The metallicity in this case will be the abundance of iron compared to hydrogen within the star.

This report will go through the numerous data steps to calibrate the data. Once the data was calibrated, light curves were reproduced for each night. These three light curves were then combined into one plot, and the period was measured using sinusoidal fitting. Since SS Psc is a RRc Lyrae star, a specific formula was used to measure the metallicity of the star. The metallicity of the star is the abundance of iron compared to Hydrogen, also known as [Fe/H], where the units are in solar units of [Fe/H] abundance. If we measure -1 for [Fe/H], this means that we have one tenth of the Sun's [Fe/H] abundance. The formula mentioned previously, courtesy of Arellano Ferro et al. (2008) and Morgan et al. (2007), was

$$Z = 52.466P^2 - 30.075P + 0.131\left(\phi_{31}^{(c)}\right)^2 + 0.982\phi_{31}^{(c)} - 4.198\phi_{31}^{(c)}P + 2.424, \tag{2}$$

where P is the period of the light curve, $\phi_{31}^{(c)}$ is a fitting coefficient and is equal to

$$\phi_{31}^{(c)} = \phi_3 - 3\phi_1. \tag{3}$$

The fitting coefficient comes from fitting the measured apparent magnitude of all three nights combined, using Fourier series equation

$$m_V(t) = a_0 + \sum_{n=1}^{N} a_n \cos\left(nx + \phi_n^{(c)}\right) \tag{4}$$

where $m_V(t)$ represents the apparent magnitude. Using Equations 2,3, and 4, the metallicity of SS Psc was found. To find the distance to the star, the absolute magnitude of it had to be found. This was found by using the equation

$$M_V = -0.961P - 0.044\phi_{21}^{(s)} + 4.447a_4 + 1.061, \tag{5}$$

where M_V is the absolute magnitude, P is the period, and $\phi_{21}^{(s)}$ and a_4 were found from fitting the Fourier series equation (Arellano Ferro et al. 2008). Once the absolute magnitude was found, the distance to the star can be found by using Equation 1. The period, metallicity, and distance to the star were then compared to literature values and the statistical significance was calculated.

2. DATA REDUCTION AND ANALYSIS

	Science Images	Dark Frames	Flat Fields
Night 1	359 at 27 seconds	10 at 27 seconds	10 at 4.5 seconds
Night 2	516 at 15 seconds, 598 at 20 seconds	9 at 15 seconds, 9 at 20 seconds	9 at 5.5 seconds
Night 3	231 at 25 seconds, 253 at 15 seconds	14 at 25 seconds, 10 at 15 seconds	10 at 0.3 seconds

Table 1. Number of science images, dark frames, and flat fields at their exposure times in the V band filter.

For all three nights of observations, dark frames, flat fields, and science images were taken and the amount of them can be seen in Tab. 1. A median combine of the dark frames and flat fields were done to create a master flat and master dark at each exposure time for each night. Both of the science images and flat fields were subtracted by the master dark to correct for hot pixels and cosmic rays. Then, the corrected science images were divided by the master flat to correct for the relative sensitivity of the CCD pixels to each other. These corrections were done using the Ubuntu terminal and the data analysis tool PyRAF (PyRAF 2019).

Once the science images were corrected, we had to solve for the SS Psc's position in each image on each night. Since the night sky moves, that means that the position of the star also moves. To correct for this, the World Coordinate System (WCS) of each each image was found by using the tool Astrometry (Astrometry 2019). After this was completed for each night, each image had Right Ascension and Declination values in the header keyworlds of each .FITS file. Once this was done, we had to measure the properties of the objects in the science images. To do this, we had to set a fixed aperture of 10 pixels around SS PSc by using the image program DS9 (DS9 2019). Then, we had to find the gain of the CCD camera, which was found in the CCD's manual and the value was 2.06 (CCD 2019). These two values were then inputted into the program Source Extractor, which returns a catalog of objects within each image (SourceExtractor 2019). We updated the parameters of Source Extractor to output the flux, flux error, and the Julian Date for each exposure. So, after these calibration steps, we had the flux, flux error, and the Julian Date for each image on each night.

In order to correct for atmospheric variability, reference stars were chosen on each night. Using Source Extractor, the flux, flux error, and the Julian Date were found for each exposure on each night. An example of the reference star's counts vs. observation time can be seen in Fig. 1. Since we had different exposures for nights 2 and 3, we had to divide the counts of each exposure by its' exposure time. This was also done for the reference stars. To apply the reference stars to SS Psc, we had to find the weighted mean of the reference star and its corresponding error. The weighted mean was

$$\mu_i^{ref} = \frac{\Sigma_j \frac{f_j^{ref}}{(\sigma_j^{ref})^2}}{\Sigma_j \frac{1}{(\sigma_j^{ref})^2}}, \tag{6}$$

where μ_i^{ref} is the weighted mean, f_j^{ref} is the flux of each exposure of each reference star, and $\sigma_j^{ref})^2$ is the error of the flux of each exposure of each reference star. The corresponding error on the weighted mean was

$$\sigma_i^{ref} = \left(\frac{1}{\Sigma_j \frac{1}{(\sigma_j^{ref})^2}} \right)^{1/2}, \tag{7}$$

where σ_i^{ref} is the weighted mean's error. Following this, the flux of each science image was scaled by the weighted mean, i.e. f_i^{sci} / μ_i^{ref}. This was only done for the flux error of each science image. Once this was done for each exposure on each night, the magnitude in the visual band was found by using the equation

$$m_V = M_{V_2} - 2.5log_{10}\left(\frac{F_1}{F_2}\right), \tag{8}$$

where m_V is the apparent visual magnitude, M_{V_2} is the absolute visual magnitude of the calibration star, F_1 is the flux of each exposure of SS Psc, and F_2 is the flux of each exposure of the calibration star. The calibration star was another star within each image and has an absolute magnitude of 8.86 mag. The flux of the calibration star was found the same was as SS Psc and the reference stars. So, for each night, a light curve of the apparent visual magnitude was plotted against each exposure's respective Julian date. The results of each night can be seen in Figs. 2, 3, and 4.

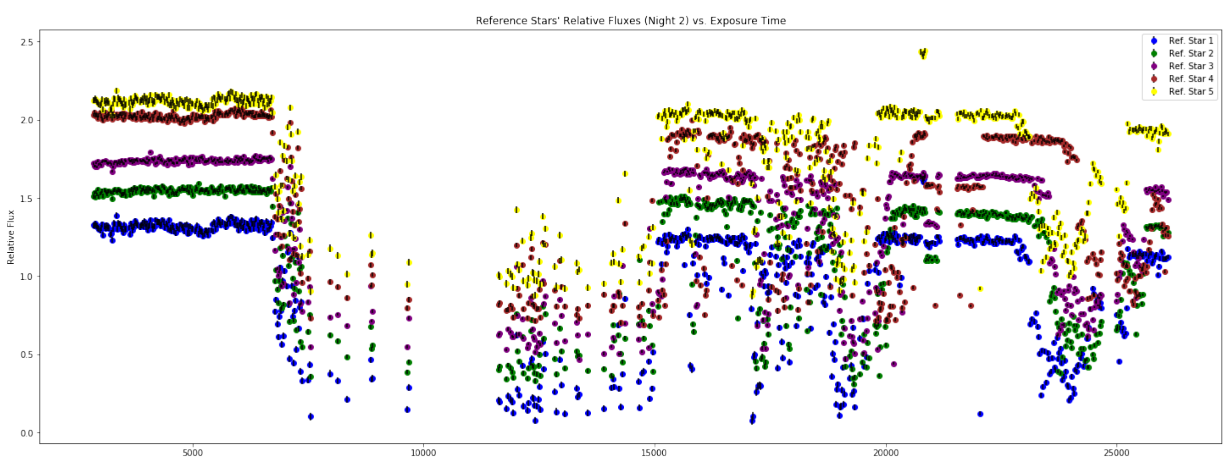

Figure 1. An example of the reference star's relative flux plotted against exposure time on night 2. Each reference star was bumped up by a constant so they can all be seen on one plot. As you can tell, there were many exposures that were affected by atmospheric conditions. So, we had to remove those exposures from the data analysis. Similar plots for nights 1 and 3 were also created.

Now that we had the apparent visual magnitude light curves for each night, we had to combine all three nights together. To do this, the time of the light curve's maximum magnitude was found for each night. Once the maximum for each night was found, a sinusoidal function was fitted to the curves of nights 2 and 3. This was done so that we can get an estimate for the period for both of those nights. The sinusoidal function that was fitted to both plots was

$$\frac{A}{4}\left(1 - V sin\left(\frac{x-c}{P}\right)\right), \tag{9}$$

where x represents the Julian Date and A, V, C, and P represent parameters. The P parameter represents the period. We measured a period of 0.3189 Days $\pm$ 0.005000 Days for night two and a period of 0.3183 Days $\pm$ 0.006000 Days for night three. Taking the average of these two periods, the measured period came out to be 0.3181 Days $\pm$ 0.007810 Days. Using this averaged period, we could shift both night 1 and night 2 so that they would be in the same phase with night 3's curve. The combined apparent visual magnitude plotted against Julian Date can be found in Fig 5.

We wanted to change Julian Dates to phase, so we changed Julian Dates to phase and corrected it so that the start of the phase occurred at the first exposure on night 1. Following this, we fitted the same sinusoidal function as in Eqn. 9 to the plot to find the period. The fitted function on the plot can be found in Fig 6. Using the P parameter once again, the period was found.

After the period was found, the metallicity could be found by using Eqn. 2. The fourier series fitting was done by one of the co-authors, and we used the fitting coefficient that they found. Using the measured period and fitting coefficient, the metallicity was found. The corresponding error to the metallicity was found by using the equation

$$\sigma_Z = \sqrt{\left(\frac{\partial Z}{\partial P}\right)^2 \sigma_P^2 + \left(\frac{\partial Z}{\partial \phi}\right)^2 \sigma_\phi^2}, \tag{10}$$

where Z is the metallicity, P is the period, and ϕ is the fitting coefficient. The final step was finding the distance to SS Psc. This was done by first measuring the absolute magnitude of it by using Eqn. 5. The corresponding error to the absolute magnitude was found by using the equation

$$\sigma_{M_V} = \sqrt{\left(\frac{\partial M_V}{\partial P}\right)^2 \sigma_P^2 + \left(\frac{\partial M_V}{\partial \phi_{21}^{(s)}}\right)^2 \sigma_{\phi_{21}^{(s)}} + \left(\frac{\partial M_V}{\partial a_4}\right)^2 \sigma_{a_4}^2}, \tag{11}$$

where M_V is the absolute magnitude, and $\phi_{21}^{(s)}$ and a_4 are fitting coefficients along with their corresponding errors. Rearranging Eqn. 1, the distance to the star was found by using equation

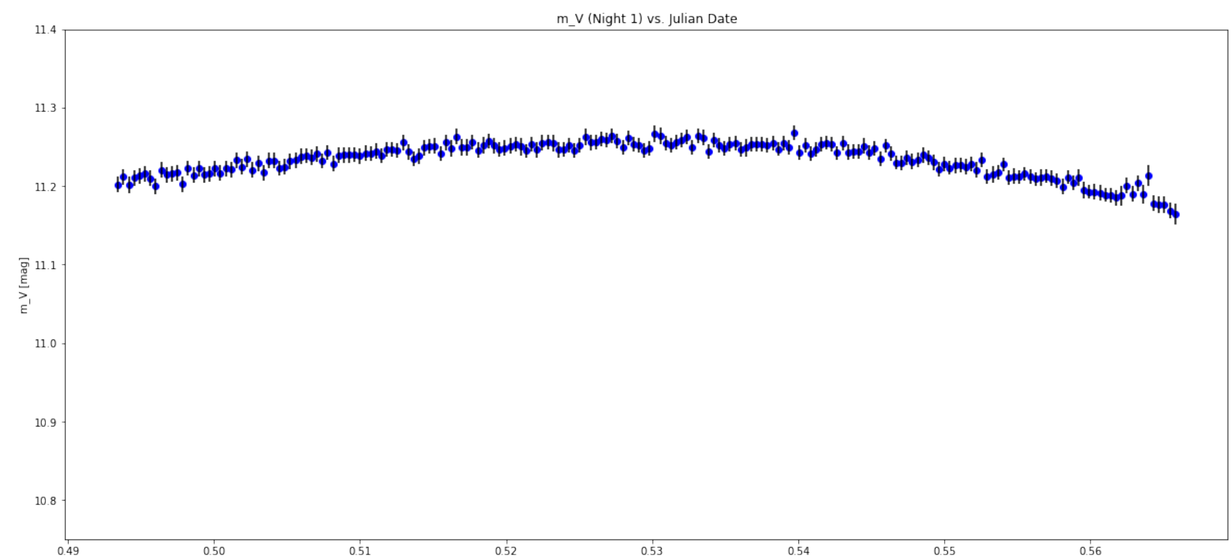

Figure 2. The apparent visual magnitude plotted against Julian Date for night 1. There is a maximum seen in this plot, which was useful in finding the period of SS Psc.

$$d = 10^{\frac{m_V - M_V + 5}{5}}, \tag{12}$$

where d is the distance in parsecs, m_V is the apparent magnitude of SS Psc, and M_V is the measured absolute magnitude of SS Psc. The distance's corresponding error was found by using equation

$$\sigma_d = \sqrt{(\sigma^2_{m_V} + \sigma^2_{M_V})\left(\frac{m_V - M_V + 5}{5}\right)^4 \left(\frac{m_V - M_V}{5}\right)^{10} ln(10)^2}. \tag{13}$$

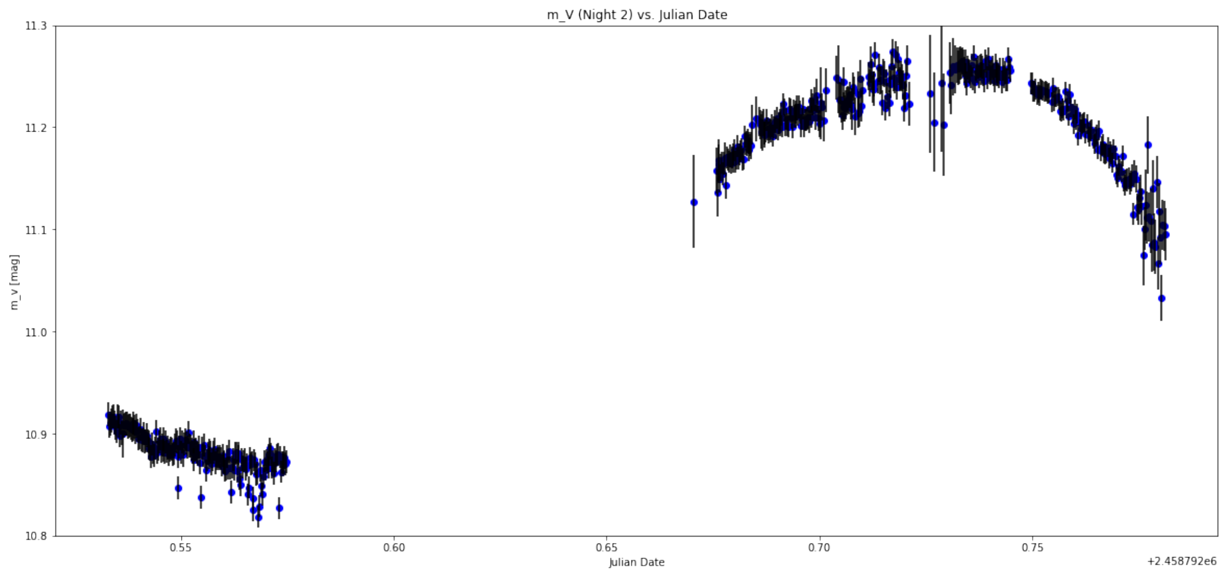

Figure 3. The apparent visual magnitude plotted against Julian Date for night 2. The gap in the middle represents exposures that were removed because of cloud cover or fluxes that significantly deviated from the other fluxes.

3. RESULTS

The three main results that were found in this experiment was the period of the apparent magnitude oscillations of SS Psc, the metallicity of SS Psc, and the distance away from SS Psc. We measured the period to be 0.325 days $\pm$ 0.00621 days. Other measurements done on this star have a period of 0.288, courtesy of Ferro et al. (2012), and a period of 0.287, courtesy of Pena et al. (2008). Both of these measurements do not have associated errors with them; however, we will assume a relatively large error of 0.1 days for each one. The statistical level for each measurement, comparing to the two literature values, were 0.36σ and 0.38σ. The statistical level was found by equation

$$\frac{|x_1 - x_2|}{\sqrt{(\sigma^2_{x_1} + \sigma^2_{x_2})}}, \tag{14}$$

where x_1 and x_2 are the measured and literature measurements along with their corresponding errors. Since we are within 3σ for each measurement, we can say that they are consistent with the literature values.

We measured the metallicity, also known as [Fe/H] abundance, was measured at -1.36 $\pm$ 0.172. Other measurements done on this star have a metallicity of 0.88 pm 0.21, courtesy of Ferro et al. (2012), and -0.2, courtesy of Pena et al. (2008). Pena et al. (2008)'s measurement does not have an associated error, so we can assume a relatively large error of 0.1. The statistical level compared to Ferro et al. (2012)'s measurement was 1.7σ and the statistical level compared to Pena et al. (2008)'s measurement was 5.8σ. So, we can say that our metallicity measurement is consistent with one of the literature values, but not consistent with the other literature value.

Lastly, we measured the distance away from SS Psc to be 999.75 pc $\pm$ 103.99 pc. Another measurement done on this found the distance to be 959 pc away, courtesy of Marsakov et al. (2018). Since this measurement does not have an associated error, we can assume a relatively large error of 50 pc. Then, the statistical level compared to Marsakov et al. (2018)'s measurements was 0.35σ. Thus, we can say that our distance measurement is consistent with the literature's measurement.

4. CONCLUSION

In this experiment, we measured the distance, metallicity, and period of visual apparent magnitude oscillations of RRc Lyrae star SS Psc. We measured a distance of 999.75 pc ± 103.99 pc, which was consistent with Marsakov et al. (2018)'s distance measurement. For the metallicity value, we found it to be -1.36 ± 0.172. This value was consistent with with Ferro et al. (2012)'s measurement; however, it was not consistent with Pena et al. (2008)'s measurement. Lastly, the period was measured at 0.325 days ± 0.00621 day, which was consistent with both of Ferro et al. (2012) and Pena et al. (2008)'s values. All of these measurements were found through rigorous data reduction and analysis. To improve upon our values, I would suggest retaking the images for another three nights without cloud cover, since we lost a considerable amount of data to atmospheric conditions. With more data points that are unaffected by the atmospheric conditions, we would be able to obtain more accurate values of the period, metallicity, and distance.

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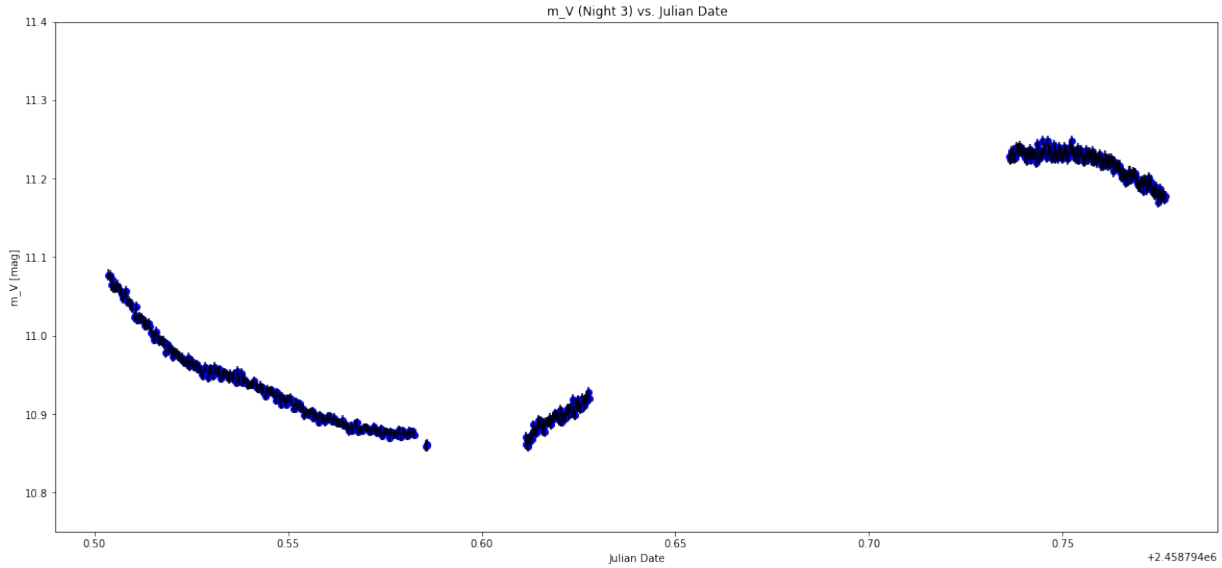

Figure 4. The apparent visual magnitude plotted against Julian Date for night 3. The gaps represent exposures removed due to cloud cover or fluxes that significantly deviated from the other fluxes. Both a minimum and maximum can be seen on the plot; however, the maximum was the important quantity that was used in finding the period.

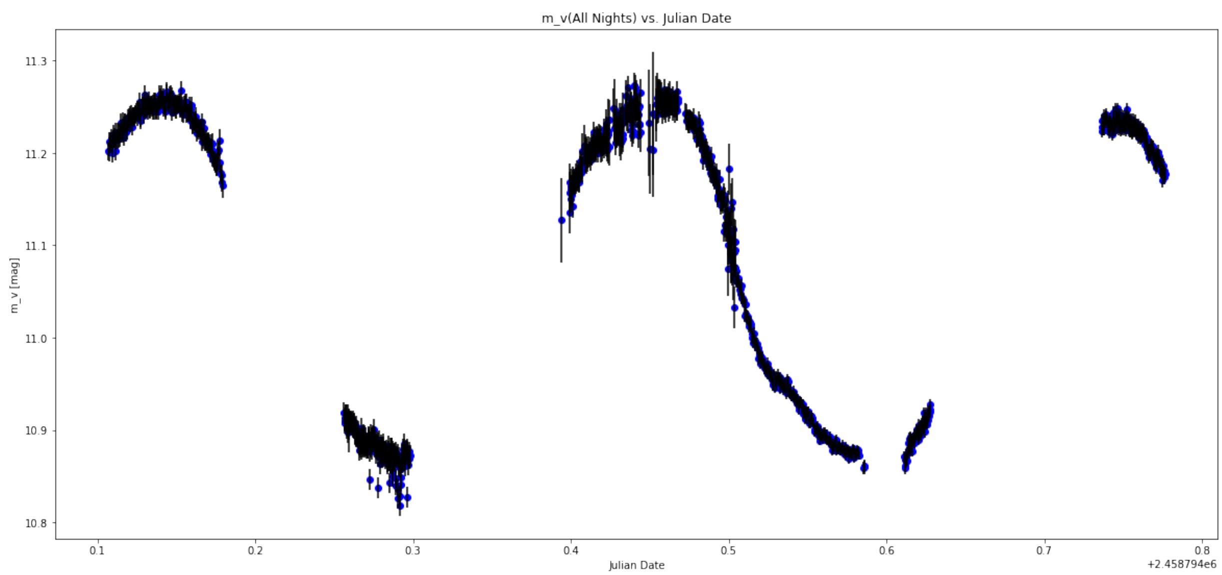

Figure 5. The apparent visual magnitude plotted against Julian Date for all nights combined.

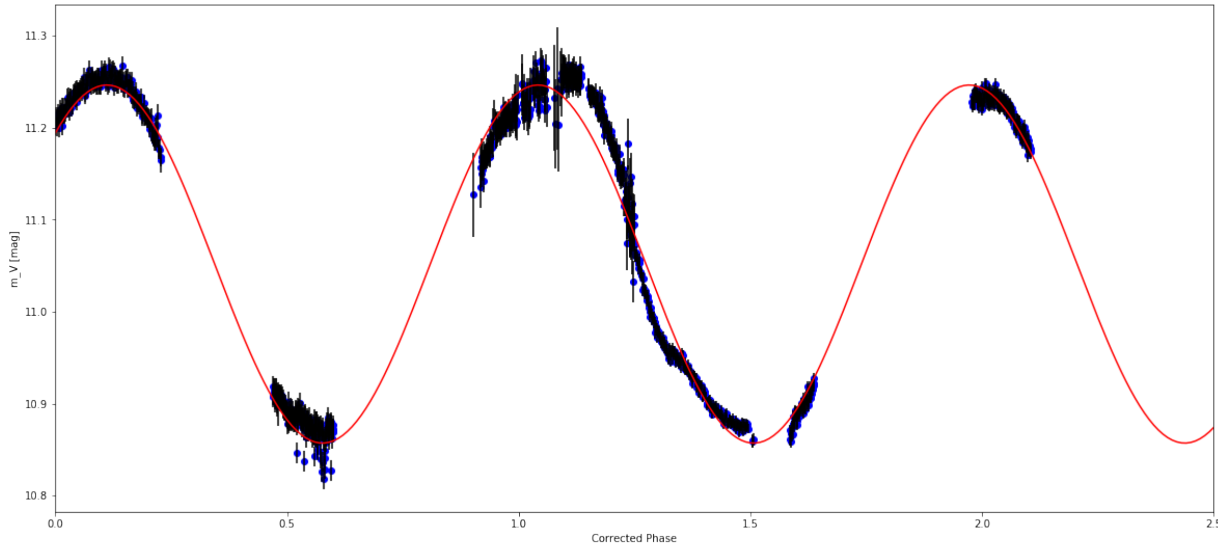

Figure 6. The apparent visual magnitude plotted against Julian Date for all nights combined along with a sinusoidal fitted to the data. As shown, the fitted curve represents the data well.