Properties of the NN Serpentis Binary Star System

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Abstract

Using the Sedgwick telescope of the LCOGT telescope network, we analyze 303 FITS (flexible image transport system) images of an eclipse along with rough estimates of the radii of white dwarfs to ascertain the apparent magnitude, Luminosity, absolute magnitude, distance, period, and orbital radius of the NN Serpentis binary.

$$m = 16.545 \pm 0.212$$
$$L = 7.131 \times 10^{26} \pm 4.387W \times 10^{26}$$
$$M = 4.178 \pm 0.267$$
$$d = 9700 \pm 630 \text{ light-years}$$
$$R = (6.41 \pm 0.07) * 10^8 m$$

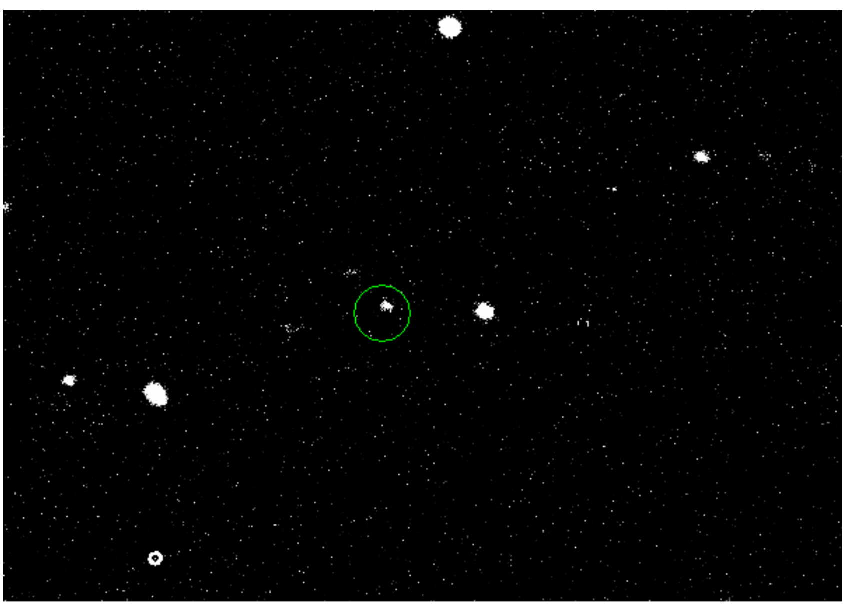

Figure 1: Field image of NN Serpentis (RA: $15^{\mathrm{h}}52^{\mathrm{m}}56.19^{\mathrm{s}}$, DEC: $12^{\mathrm{o}}54^{'}47.4^{''}$)

1 Introduction

Half of all stellar systems are comprised of at least two stars(Filippenko, *Understanding the Universe*). It is difficult to accurately determine the properties of an isolated star, but with the ability to observe the periodic eclipses from a binary star system, orbital data can be used to measure many otherwise impossible characteristics of the stars. Thus, most of our knowledge of stellar masses is obtained from binary systems. The NN Serpentis binary star system is a system with two very close stars, a small white dwarf and a much larger red dwarf. The angle of declination of their orbit is nearly 90 degrees, at $89.6 \pm 0.2°$ (Parsons et al. 2009), which means the primary eclipse has a large difference in magnitude from the non-eclipsing state.

When two stellar bodies are in close proximity to one another, they orbit each other in a system known as a stellar binary. If the two stars in a stellar binary are oriented such that one of the stars obscures the other, it is called an eclipsing binary.

In an eclipsing binary, the amount of light received from the system is at a maximum when both stars are visible, and has sharp declines in brightness during the eclipses(see Figure 2).

Our goals were to obtain the distance and orbital radius of the system using a combination of LCOGT telescope network images and known temperature data from estimates and prior research. We also used the upper and lower bounds of the radii of white dwarfs to provide upper and lower bounds for the luminosity of the white dwarf star, NN Serpentis A.

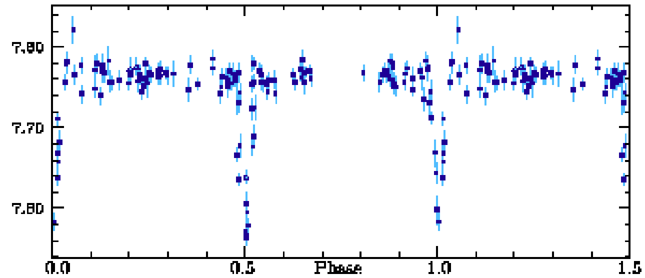

Figure 2: Light curve of an eclipsing binary found by HIPPARCHOS (Kruszewski, Semeniuk. 1999)

2 Observation and Data Collection

We gathered images from the LCOGT telescope network of the area of sky containing NN Serpentis. Our data set consisted of 303 FITS images recorded over the course of about four hours. These images were 30 second exposures taken during mostly clear skies with a photon to electron gain of 1.4.

We also estimated that the size of white dwarfs ranged from 0.8-2% of a solar radius(citation).

The temperature and radius of NN Serpentis A were:

$$T = 57000 \pm 3000K$$

and

$$R = 0.014 \pm 0.006 R_{\odot}$$

(Parsons et al. 2009). We also found used measurements of the masses of NN Serpentis A and NN Serpentis B, which where:

$m_A = (0.535 \pm 0.012) M_\odot$
$m_B = (0.111 \pm 0.004) M_\odot$

3 Data Analysis and Results

We analyzed the LCOGT FITS images containing the NN Serpentis binary and chose one of them in which the system was clearly visible, and used it a master image. We then located the system in each of the other images and shifted the coordinates so that each image containing NN Serpentis had it at the same pixel location within the image. Out of the 303 images, 291 contained a reliable image of NN Serpentis. Then, we took the brightest five stars in each image, measured the apparent flux that the detector picked up, and compared it to the master image. The mean of the ratios between these was used to normalize each image, thereby mitigating most of the error in flux caused by atmospheric conditions and the varying zenith angles at which the images were taken.

$$gain = \frac{f_1}{f_2}$$

Then, we investigated the data around $T = 0.14$ and found that the images around that time were blurry, which explains the wide range of outlier values in that time range. We omitted that data for further calculations.

With all of our images normalized, positioned and corrected, we wrote an image matching program to use along with Source Extractor to output the flux through the detector in the pixel position of NN Serpentis into a cat file. By using the timestamps contained in the header of each FITS image, we can generate a plot of the light curve, with the error in flux given by the nature of the detector(see figure 2).

3.1 Obtaining the apparent magnitude of NN Serpentis A

The apparent magnitude is a measurement of how bright a star appears in the sky from earth. It is a logarithmic scale with brighter objects having lower magnitudes. A difference of 1 point of magnitude corresponds to a change in brightness by a factor of $\sqrt[5]{100}$, or about 2.512 (Chromey, To Measure the Sky, pg. 27).

The first thing to note is that during the timespan of the eclipse, the flux through the detector should solely be that of the red dwarf. Because the red dwarf is much dimmer than the white dwarf, the average flux through the detector throughout the majority of the orbital period should primarily come from the white dwarf. We can subtract the flux caused by the red dwarf, and find the average detector flux of the white dwarf.

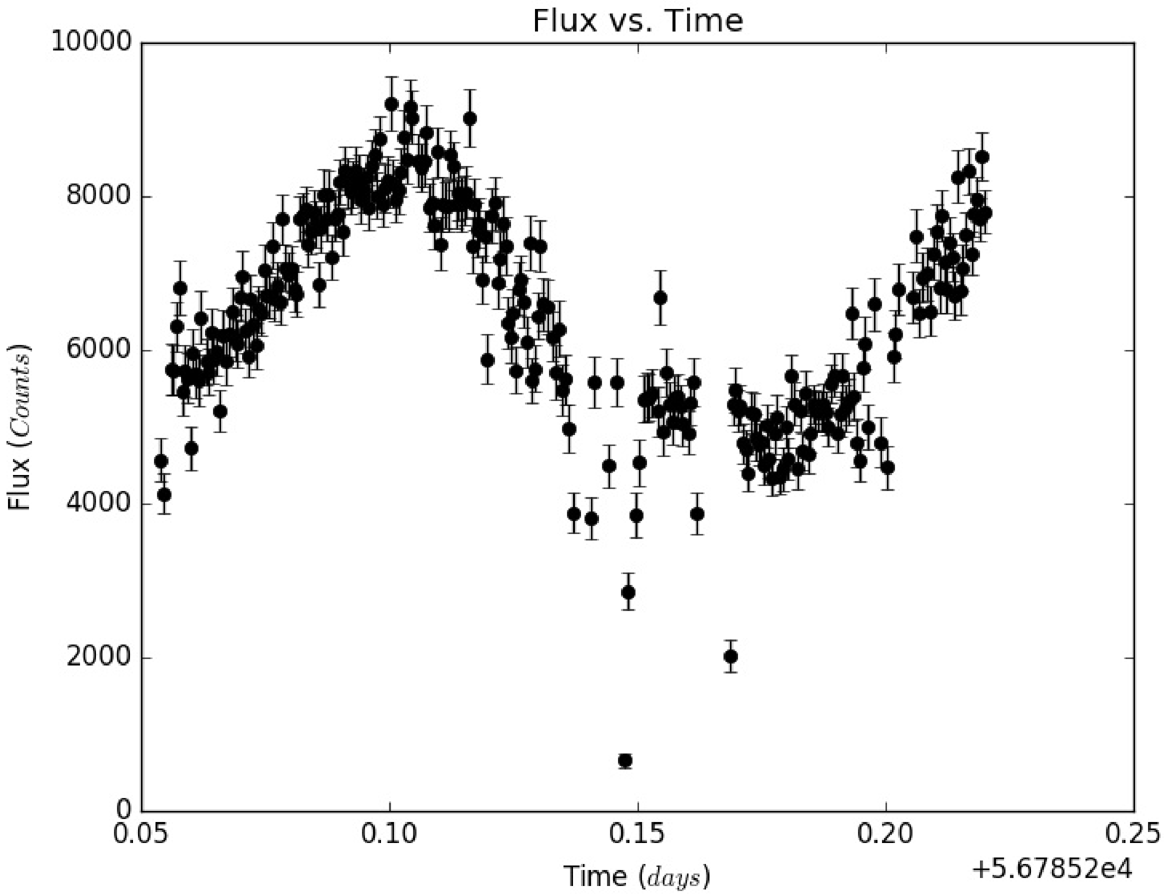

Figure 3: Light curve of NN Serpentis over the course of 4 hours

We can take the average of the flux during non-eclipse times and then take the standard deviation as our error. For each data point:

$$f_{total} - f_{reddwarf} = f_{whitedwarf}$$

So if we take the mean and standard deviation:

$$\overline{f_{whitedwarf}} \pm \sigma_{whitedwarf}$$

before correcting for the electron to photon gain of 1.4, we have:

$$\overline{f_{whitedwarf}} \pm \sigma_{whitedwarf} = 4200 \pm 300 counts$$

Now that we have the mean flux per data point, we can find the apparent magnitude, given by:

$$m = -2.5\log_{10}\left(\frac{counts/gain}{time}\right) + C$$

where the gain of the detector is 1.4, and time is the 30 second exposure time of each FITS image and C is the zero point. We find the zero point by using a reference star for which we already know its apparent magnitude, and have flux count data in the same images as NN Serpentis. We used sky-map data for USNOA2 0975-080027092 and the flux from that star in our FITS images to find the zero point, which is:

$$C = 21.55 \pm 0.21$$

The error of the apparent magnitude measurement comes from the error of the flux, zero point, gain, and exposure time:

$$\delta m = \sqrt{0.434((\frac{\delta f}{f})^2 + (\frac{\delta t}{t})^2 + (\frac{\delta g}{g}))^2 + (\delta C)^2}$$

However, the time has an error of $\pm 0.05s$, an error of 0.1%. The gain also has a negligible error, so the error in the apparent magnitude is only dependent on the error in photon flux and the error involved in calculating the zero point. Thus, the corrected error equation is:

$$\delta m = \sqrt{(0.434\frac{\delta f}{f})^2 + (\delta C)^2}$$

Thus, the apparent magnitude is:

$$m = 16.545 \pm 0.212$$

3.2 Obtaining the Luminosity of NN Serpentis A

White dwarfs radiate roughly as black bodies; we are able to use the Stefan-Boltzmann Law to find the luminosity of NN Serpentis A.

$$L = 4\pi R^2 \sigma T^4$$

If we use the temperature value $57000 \pm 3000K$ (Parsons et al. 2009) and the range of radii for the average white dwarf 0.8-2.0% of a solar radius(citation), we find that the luminosity is:

$$L = 7.131 \times 10^{26} W$$

with the error in luminosity given by:

$$\frac{\delta L}{L} = \sqrt{2(\frac{\delta R}{R})^2 + 4(\frac{\delta T}{T})^2}$$

This yields an error of:

$$\delta L = 4.387 \times 10^{26}$$

This is an extremely large error, but if we assume NN Serpentis A has the radius of a typical white dwarf, we can obtain a much more accurate estimate. Thus, our luminosity is:

$$L = 7.131 \times 10^{26} \pm 4.387W \times 10^{26}$$

3.3 Finding the Absolute Magnitude from the Luminosity

Using the Luminosity found in the previous section, we are now able to find the absolute magnitude of NN Serpentis A.

Absolute magnitude is a measure of the intrinsic brightness of a celestial object. It is the apparent magnitude an object would theoretically have if it was located 10 parsecs away from the observer, assuming no depreciation of starlight due to obstructions or gravitational effects. This is useful for placing objects on a common scale to compare their brightness with both their own apparent brightness, as well as the apparent and absolute brightness of other stellar objects. Our instruments detected light in the visual band of wavelengths centered around 445 nm. There is a slight discrepancy between the ratio of the fluxes in the Visual band, and the absolute bolometric magnitude, which takes into account energy radiated at all wavelengths, whether or not they are visible.(csep10.phys.utk.edu) The absolute magnitude is given by the equation:

$$M = 4.85 - 2.5\log_{10}\left(\frac{L}{L_{\odot}}\right)$$

Given that the luminosity of the sun is:

$$L_{\odot} = 3.846 \times 10^{26} W$$

and the Luminosity, from the previous section is:

$$L = 7.131 \times 10^{26}$$

the absolute magnitude of NN Serpentis is:

$$M = 4.178$$

The error in absolute magnitude should be the same as the fractional error in Luminosity:

$$\delta M = 0.434\left(\frac{\delta L}{L}\right)$$

Thus, the absolute magnitude is

$$M = 4.178 \pm 0.267$$

3.4 Measuring the Distance to the NN Serpentis Binary System

The absolute magnitude, along with the apparent magnitude found in a section 3.1 can be used to ascertain the distance to the system. Because the apparent magnitude is a measure of how bright the star appears from our distance, and the absolute magnitude is a measure of how bright the star should appear from a set distance, we can measure the discrepancy between the two to calculate the distance to NN Serpentis. The equation relating apparent magnitude, absolute magnitude, and distance is:

$$m - M = -5 + \log_{10} d$$

Solving for distance, we get:

$$d = 10^{\frac{(m-M+5)}{5}}$$

Using the absolute magnitude and apparent magnitude obtained in section 3.1 and 3.4, we get:

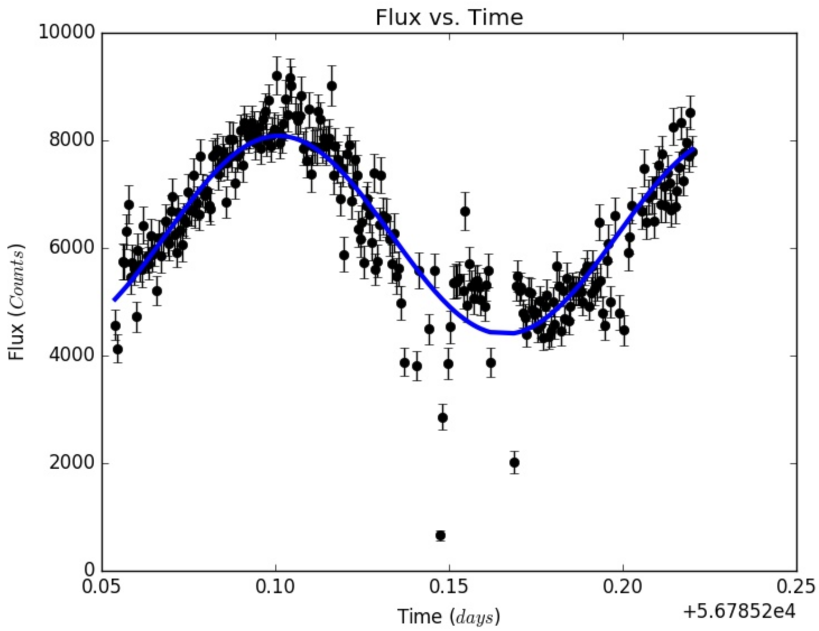

Figure 4: Sine wave fitted to the Light curve of NN Serpentis

$$d = 2974.40pc$$

The error in the distance comes from the error in the apparent and absolute magnitudes as such:

$$\frac{\delta d}{d} = \sqrt{(\frac{\delta m}{m})^2 + (\frac{\delta M}{M})^2}$$

So our distance to the NN Serpentis binary is:

$$d = 2974.40 \pm 194.96pc$$

or

$$d = 9700 \pm 630 \text{ light-years}$$

This value, when compared to the actual distance to the NN Serpentis binary:

$$d = 1670 \pm 150 \text{ light-years}$$

(Parsons et al. 2009) is off by almost an order of magnitude. It is likely that the data we have for the radius is the culprit since it has the greatest fractional uncertainty. Other potential factors include the possibility the apparent magnitude is not accurate due to dust obscuring our line of sight to the binary or atmospheric conditions not being as clear as the FITS file metadata would suggest.

3.5 Estimating the Orbital Radius of the NN Serpentis Binary System

The distance between NN Serpentis A and B can be obtained using only the masses of the two bodies and the period of their orbit. We can fit a sine wave to the light curve to obtain the period of the orbit (see figure 3). The period of the fitted sine curve is:

$$P = 0.1275 days$$

Converted to hours this is:

$$P = 3.06 hours$$

Now that we have the period, we can use it with the masses of NN Serpentis A and B in the equation for Kepler's Third Law:

$$P^2 = \frac{4\pi^2 R^3}{G(m_A+m_B)}$$

Solving for R we have:

$$R = \sqrt[3]{\frac{P^2 G(m_A+m_B)}{4\pi^2}}$$

The sources of error of the orbital radius are the period and the two masses of NN Serpentis A and B:

$$\frac{\delta R}{R} = \sqrt{\frac{2}{3}(\frac{\delta P}{P})^2 + \frac{1}{3}(\frac{(\delta m_A)^2+(\delta m_B)^2}{(m_A+m_B)^2}}$$

However, the period curve fit has a negligible error of 0.3% , so the masses are the only sources of error.

$$\frac{\delta R}{r} = \frac{1}{\sqrt{3}}(\frac{\delta m_t}{m_t})$$

Thus, the final result for the orbital radius of the NN Serpentis binary is:

$$R \pm \delta R = (6.41 \pm 0.07) * 10^8 m$$

4 Conclusions

By analyzing the LCOGT FITS files in conjunction with known values of temperature, radius, and masses of the NN Serpentis binary star system, we found:

$$m = 16.545 \pm 0.212$$
$$L = 7.131 \times 10^{26} \pm 4.387W \times 10^{26}$$
$$M = 4.178 \pm 0.267$$
$$d = 9700 \pm 630 \text{ light-years}$$
$$R = (6.41 \pm 0.07) * 10^8 m$$

4.1 Error Analysis and Improvements

The biggest sources of error were the radius of the white dwarf in the calculation of the radius. If we had used an established measurement or collected experimental data to find the radius of NN Serpentis A, we would have obtained a much more accurate result for the Luminosity, which would have led to a more accurate absolute magnitude, and further calculations dependent on the radius. Another large source of error was the inaccuracy in the apparent brightness. Although we had very low error in the apparent magnitude, it is likely that there was a source of systematic error influencing our results. There could have been a cloud of dust blocking starlight, or atmospheric conditions that persisted throughout the four hour data collection period that influenced the result. To find out if there were obstructing particles, we could take data through a larger range of wavelengths using different filters to obtain the bolometric apparent magnitude, and then compare it with spectroscopy data to measure discontinuities in the spectrum that are characteristic of certain elements. That way you can ascertain what constitutes the cloud and correct for the discrepancy. Any problems caused by atmospheric conditions could be solved by simply taking a longer timescale of data.

5 References

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