Sample lab report

Here is a sample lab report for an observing exercise where the brightness of a specific variable star (Delta Cephei) was tracked over the period of about a month. Once the observations were complete, they were plotted on a graph in order to estimate the period of the star's variability and use it to determine other properties.

While this is not like any exercise in the lab manuals, your main takeaways here are to see how the report is *organized* and how the questions are answered in terms of detail. As always, refer back to the lab report guidelines in your manual, as well as available rubrics. Depending on your course, the standards for your answers may be different (less or more detail). For instance, this particular exercise had no estimate of uncertainties. It is important that you follow the specific requirements laid out in the manual.

The context behind the exercise:

When we observe stars from Earth, their apparent brightness is reduced by a factor of $1/\text{distance}^2$. As a result, if we determine how bright the object appears, and compare it to how bright it actually *is*, we can determine its distance. In astronomy, this is typically done through the *magnitude system*.

Cepheid variable stars have a relationship between their periods and actual brightness. As part of the exercise, the hypothetical "lab manual" provided a diagram from "Calibrating the Cepheid period-luminosity relation from the infrared surface brightness technique" by Storm et al. 2011 (specifically Figure 9). This diagram was used to convert the measured period P into an absolute magnitude M of the star (a measure of how bright the star actually is).

Once the absolute magnitude was determined, it could be subtracted from the *apparent* magnitude m. The quantity $(m - M)$ can be used to calculate the distance using a specific relationship.

Since we were observing a source with a repeating pattern, some additional analysis was requested. As an estimate of how "good" the observations and period estimate were, the student was also required to plot a "phase" diagram, which basically plots all the repeats on top of each other. For bad observations and estimates, the points would appear disorganized and random.

As part of the data section, the observations of Delta Cephei and the "light curve" needed to be included. For additional context, here are the hypothetical Analysis and Discussion questions from the "manual":

Analysis

(1) Estimate the period of variability, P, of the star from the graph, using both maximum and minimum brightness and taking the average.

(2) Using the period you determined, convert the number of days into a *phase* using:

$$\phi = \frac{(t - t_0)}{P} - N_P \tag{1}$$

where N_P is the number of complete periods since t_0 (basically the first term in the equation rounded down to the nearest whole number). Show your work.[1]

(3) The accepted period of Delta Cepheii is 5.366 days[2]. Recalculate the phase and make a graph plotting your data with the results of Question 2 as well as with the recalculated phase.

(4) Use the provided plot of the period-luminosity relation from Storm et al. 2011 to estimate the absolute magnitude from your calculated period, then estimate the distance to Delta Cephei assuming an apparent magnitude of $m = 3.95$. You can either use the distance modulus equation or look it up on the provided graph.

Discussion

- How well does your estimated period agree with the accepted value?
- Compare the plots of phase vs brightness. If your measurements and estimated period were reasonably accurate, the points of the phase plots using both periods should organize themselves into distinct, well-ordered curves. Based on the appearance of the plot, how good was your estimate?
- The accepted distance to Delta Cephei is 887 light-years (272 parsec). How well did your value agree?

[1]Note: phase is a dimensionless quantity; it represents the time of observation as a fraction of one complete cycle

[2]https://www.aavso.org/vsots_delcep

Determining the Distance to Delta Cephei

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Objective

In this exercise, I tracked the brightness of the variable star Delta Cephei over the course of a month in order to determine its period. In the process I explored how well I could track brightness with just my naked eye, and how use my observations to measure the distance to the star. While it was not perfect, I found that I was able to judge the brightness well enough that I saw a consistent pattern with a period very close to the accepted value.

Introduction

Some stars in certain stages of their life will become unstable, which can cause their brightness to vary regularly with time. One of the more important types of variable stars are Cepheid variables. Henrietta Swan Leavitt, one of the group of woman astronomers known as the "Harvard computers" was working on quantifying stellar magnitudes from photographs, and discovered in 1912 that Cepheid variables have very regular periods that are directly related to their actual brightnesses[1]. This allows us to determine the intrinsic brightness of these stars independent of direct measurement. As a result, their distances from us can be calculated through the distance modulus:

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

where D is the distance to the star, M the absolute magnitude at 10 pc from the star, and m the observed magnitude from Earth.

Because the relationship between brightness and variable period is so well-defined, this makes them important *standard candles*: objects that astronomers can use to determine distances[2]. These stars are typically bright enough that they can be used to measure distances to nearby galaxies.

Delta Cephei was the first Cepheid variable identified and is the "archetype" of the class[3]. It is a convenient target for naked-eye estimation of its brightness since it forms the point of a triangle with two nearby stars that have approximately the same brightnesses as Delta Cephei's maximum and minimum values of 3.5-4.4 mag[3].

Observations of a target that follows a regular repeating pattern can be plotted on a *phase diagram*, which plots brightness relative to fraction of period cycle. If the data points organize themselves into a clear wave shape, then the period of variability is accurate. If the points are disorganized, than the estimate of the period is incorrect.

As part of this exercise, I am assuming that the only factor affecting the average apparent magnitude of Delta Cephei is distance, and that there is no reduction from extinction (absorption by the interstellar medium between it and Earth).

Procedure

For each observation I located Delta Cephei and compared its brightness to the two nearby stars Epsilon and Zeta Cephei. I estimated its brightness on a scale where Zeta Cephei had a brightness of 1, and Epsilon Cephei a brightness of 5 (smaller number = brighter) representing an "eye magnitude." 26 Observations were taken between July 31 and August 27, 2024 when weather and location allowed. For consistency, I tried to take my measurements at approximately the same time of day.

Once the observations were complete, I plotted my estimated brightness values of Delta Cephei against the time of observation to see how the brightness varied with time. This allowed me to roughly determine the variable period of the star. First, I averaged the time between peaks in brightness by measuring the time between the first and last peak, and then divided the number of days by the number of peaks in that time period. Then I repeated the calculation for the number of troughs (minima) and took the average of the two estimates as my period.

Once I had my estimate of period, I calculated the phase of each observation and made a phase diagram for the star. As a comparison, I also calculated the phase of each observation using the accepted period and plotted it on the same graph.

I then estimated the absolute magnitude of the star by using the provided graph of the "luminosity-period" relationship for Milky Way Cepheid variable stars, and used the distance modulus to determine its distance.

Data

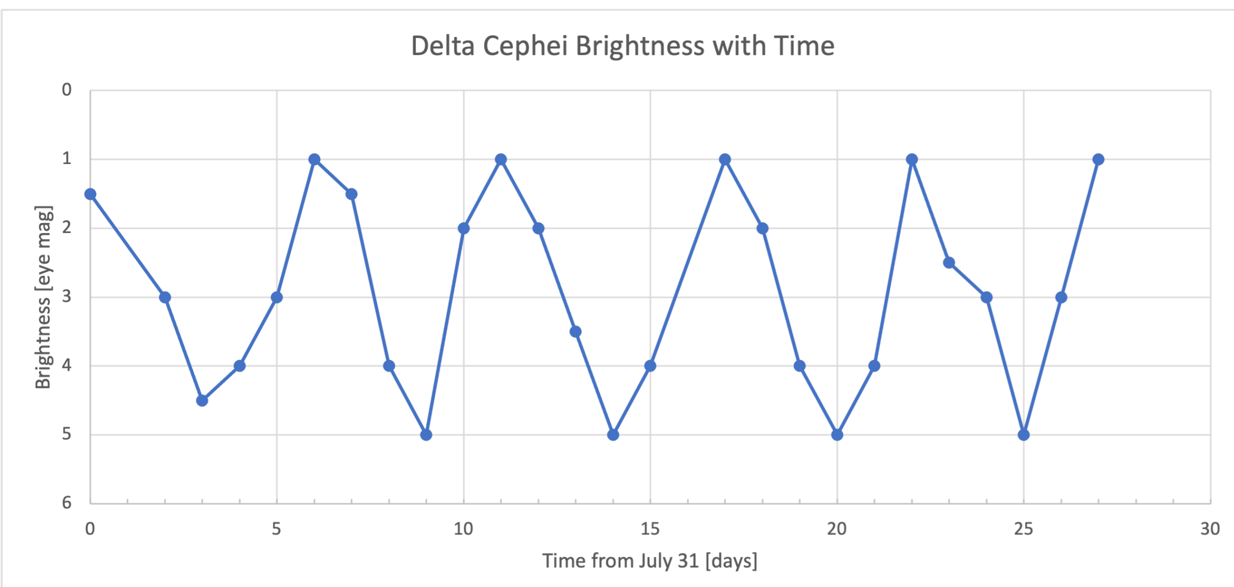

Figure 1: Delta Cephei Light Curve

Table 1: Observations

Obs Date	# Days	Brightness [eye mag]	Phase (Measured)	Phase (Accepted)
31-Jul	0	1.5	0	0
02-Aug	2	3	0.367	0.373
03-Aug	3	4.5	0.550	0.559
04-Aug	4	4	0.734	0.745
05-Aug	5	3	0.917	0.932
06-Aug	6	1	0.101	0.118
07-Aug	7	1.5	0.284	0.305
08-Aug	8	4	0.468	0.491
09-Aug	9	5	0.651	0.677
10-Aug	10	2	0.835	0.864
11-Aug	11	1	0.018	0.050
12-Aug	12	2	0.202	0.236
13-Aug	13	3.5	0.385	0.423
14-Aug	14	5	0.569	0.609
15-Aug	15	4	0.752	0.795
17-Aug	17	1	0.119	0.168
18-Aug	18	2	0.303	0.354
19-Aug	19	4	0.486	0.541
20-Aug	20	5	0.670	0.727
21-Aug	21	4	0.853	0.914
22-Aug	22	1	0.037	0.100
23-Aug	23	2.5	0.220	0.286
24-Aug	24	3	0.404	0.473
25-Aug	25	5	0.587	0.659
26-Aug	26	3	0.771	0.845
27-Aug	27	1	0.954	0.032

Analysis

(1) Taking the first observation as a peak, I counted 5 repeats over 27 days, which results in a period of $27/5 = 5.4$ days. Using the minimum brightnesses, I counted 4 repeats over 22 days for a period $22/4 = 5.5$ days. The average period over my measurements is therefore 5.45 days.

(2) My values for the phase are recorded in Table 1. Sample calculation of phase using

August 8:

$$\frac{(8-0)\text{ days}}{5.45\text{ days}} = 1.468.$$

Subtracting the whole number yields a phase of $\phi = 0.468$.

(3) My values for phase using the accepted period are recorded in Table 1. Plotting the brightness vs phase for both periods gives the following plot:

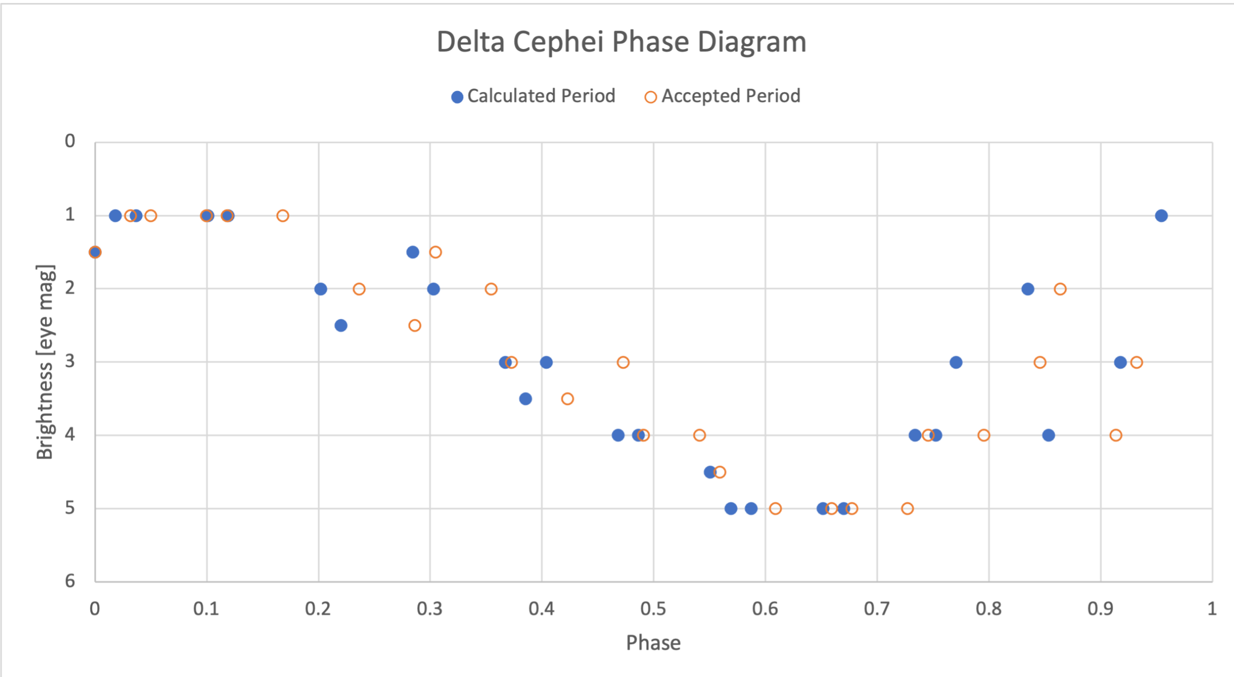

Figure 2: Delta Cephei phase diagram

(4) Using my period of 5.45 days, this produces an absolute magnitude of $M = -3.3$ from the provided luminosity-period graph. Delta Cephei has an average apparent magnitude of 3.95, this results in a distance modulus of $(m - M) = 3.95 - (-3.3) = 7.25$. Using the provided graph of distance vs distance modulus, I get a distance of approximately 300 pc.

Discussion

My result for the period of Delta Cephei was 5.45 days, which differed from the accepted value of 5.366 by approximately 0.08 days (or approximately 2 hours). This is a difference of only 1.5% of the accepted period, which is quite close. If I had observed the star for a longer period of time I may have been able to improve my estimate.

The brightness plotted against phase using both my estimate and the accepted period are smooth, well-ordered curves. This shows that my estimates of brighness were consistent throughout the observations. The overall wave shape in the plot also shows the same pattern as the example cepheid variable in the manual.

Using the accepted value in the phase calculation does not show much difference, except near the end of the cycle. In this area, the points are clustered a bit tighter when using the accepted period, and the last point has been shifted to the early part of the diagram. According to my table, this was the August 27 observation, which has an assigned brightness of 1. since my estimated period was a little long, it makes sense that a late observation at the peak brightness might have been shifted backwards in terms of phase when using my estimate. Overall, the difference between the two curves is small and serves to show that my result is a good estimate of the period.

My estimate of the distance using the provided chart was 300 pc, as compared to the accepted value of 272 pc. This was a discrepancy of 28 pc, which is almost 10% of the accepted distance. This is a much larger gap than my period measurement. However, since magnitudes are on a logarithmic scale, a small discrepancy in magnitude can add up to large discrepancy in distance. Since the distance was overestimated, it is possible that either the estimated average value of $m = 3.95$ was slightly too dim, or the estimate of $M = -3.3$ from the luminosity-period relation plot was too bright. The former prediction is consistent with interstellar extinction, and is most likely the source of the discrepancy. My estimate assumed that there was no extinction in Delta Cephei's apparent magnitude.

Overall, my observations were successful. While my distance estimate was off by 28 pc, my period estimate was within 2 hours of the accepted value. I was surprised that I was able to judge the brightnesses my naked eye so well that my estimate of the period was only 2 hours off.

Conclusions

I succeeded in my attempt to measure the period of variability of Delta Cephei, obtaining a period within 2 hours of the accepted value. By applying the relationship between absolute magnitude and period of Cepheid variables, I obtained a distance to Delta Cephei of 300 pc. While this value was off by nearly 30 pc, this exercise did demonstrate an important technique that astronomers use to determine distances in the nearby universe.

References

[1] The Encyclopedia Brittanica, "Henrietta Swan Leavitt," url: https://www.britannica.com/biography/Henrietta-Swan-Leavitt, accessed August 20, 2024.

[2] Paul M. Sutter, "Astronomy Jargon 101: Standard Candles," https://www.universetoday.com/152210/astronomy-jargon-101-standard-candles/, accessed September 22, 2024.

[3] Kerri Malatesta, "Delta Cephei," url: https://www.aavso.org/vsots_delcep, accessed September 21, 2024.