

How far to the Small Magellanic Cloud?¹

1 Introduction

Cepheid variable stars are an important step on the distance ladder to far away galaxies. They are necessary in establishing the cosmic distance scale between galaxies since they are used to calibrate other methods of distance measurement used at great distances where Cepheids are too faint to be seen. In this exercise you will use some historic data to calculate the distance to the Small Magellanic Cloud (SMC), one of the satellite galaxies of the Milky Way. In the process you will trace the path of some astronomical history.

Cepheid variable stars change in brightness with a period of a few days to about 100 days. In a study of Cepheids in the SMC Henrietta Leavitt discovered a direct correlation between the length of the period and apparent brightness (“little m ”) of the stars. Longer period stars were brighter than shorter period stars. Since all stars in the SMC are roughly the same distance away, it follows that apparently brighter stars are in fact intrinsically more luminous. Hence, longer period stars must be intrinsically brighter than short period stars. The only wrinkle here is that we know m (“little m ”), the apparent magnitude but not M (“big M ”), the absolute magnitude. If we knew M , we could calculate the distance from the distance modulus, $m - M$. In this exercise you will trace the steps and missteps in the history of this distance determination. There are seven steps necessary to complete this work:

1. Reduce the data of four stars in the SMC and obtain values of m_V and $\log P$.
2. Add your data to Table I and plot all the data on the graph provided or in an Excel chart.
3. Draw the best straight line fit to your plot either with a ruler or in Excel.
4. Now plot the data from Table II on the same graph or on the same Excel chart as Table I.
5. Draw the best straight line fit to your plot either with a ruler or in Excel.
6. Obtain a value of $m - M$ for the SMC as outlined below and complete the calculations of distance.
7. Figure Baade's correction for the Cepheid I distance modulus.

2 Data Reduction (Four Data Points)

Table I lists most of Henrietta Leavitt's data for the Cepheids in the SMC. The column HV contains the catalog number for each star while $\log P$ is the logarithm of the period in days and m_V is the apparent visual magnitude of the star. Just so you will obtain a feel for how the data in this table was obtained and understand the work Leavitt did to produce Table I, four data points are missing. You will determine those values from the light curves of those four stars before graphing all the data.

The data pipeline was a very long one. You will work with light curves but they are at the end of that pipeline with a most of the work coming well before them. Here is how they were produced. The SMC galaxy was photographed several times a night over many months. Those observations consisted of photographs showing many stars including the Cepheids. The date and time of the photographs were precisely recorded. Leavitt then compared the brightness of the Cepheids in each photograph to already established comparison stars of constant magnitude, thus determining the apparent magnitude of each Cepheid at the time of observation. Then Leavitt plotted the apparent magnitude as a function of time. She then drew a smooth curve fitting the data and producing the light curves you will be using. On each light curve Leavitt measured the times between maximum light over many cycles from which she deduced the period. In addition she measure the maximum and minimum brightness to calculate an average apparent magnitude. Her results are found in Table

I. Four of the light curves she obtained are provided for you to complete the data reduction and add your results to the values in Table I. Your instructor will provide tips on how to best reduce the light curves.

Record all of your measurements for this part on your own paper and submit that data page with the rest of your work. For each of the four light curves for Cepheid variables, estimate the apparent magnitudes at maximum and the apparent magnitudes at minimum to the nearest 0.1 magnitude. Take the average of these two values to get an estimate of each star's brightness (m_V). Find the period (P) of each star from the interval between successive maxima. If more than one full cycle is represented on the graph, the careful astronomer would use as many periods as possible. Why? Tell your instructor why. Take the logarithm of the value each period.

3 Plotting Henrietta Leavitt's Data

Table I list the apparent magnitude of the Cepheids in the SMC and the log of the period of light variation in days. Since these stars are all at the same distance, the distance modulus (even though we don't know what it is) is the same for all of these stars. Thus we can plot a period-magnitude (luminosity) relation even though we cannot properly mark the vertical axis with absolute magnitude.

Table I. Apparent Magnitude of Cepheids in the SMC

HV	log P	m_V	HV	log P	m_V
2019	0.21	16.8	2060	1.01	14.3
2035	0.30	16.7	1873	1.11	14.7
844	0.35	16.3	1954	1.22	13.8
2046	0.41	16.0	847	1.44	13.8
1809	0.45	16.1	840	1.52	13.4
1987	0.50	16.0	11182	1.60	13.6
1825	0.63	15.6	1837	1.63	13.1
1903	0.71	15.6	1877	1.70	13.1
1945	0.81	15.2			

Now plot your data and the data from Table I on the graph paper provided. Draw a best-fit straight line through your data points. Label this line "Leavitt." This plot gives us an estimate of how period and absolute magnitude are related. We simply don't know the correct scale because we used apparent magnitudes rather than absolute magnitudes in the plot.

4 Shapley's Calibration

Harlow Shapley was able to determine a period-luminosity relation for Cepheids in the halo of our galaxy by studying the Cepheids in the globular clusters. Using statistical information about the motions of stars in globular clusters to determine their distances, he could then calculate the absolute magnitude of the stars and plot a period-luminosity relation. Shapley's results are given in Table II. Neither Shapley nor Leavitt knew that there were two types of Cepheids, those with low metallicity (metal is the term stellar astronomers use for any element heavier than helium) and those with a composition similar to our Sun that has about 2% metallicity. For that reason it was reasonable to assume the stars in the SMC followed the same period-luminosity relation as those in our galactic

halo. That is exactly what Henrietta Leavitt did in 1912 to obtain the very first distance to another galaxy.

You will follow in her footsteps. Plot Shapley's data on your period-luminosity graph and draw a straight line to fit those points. Label this line "Shapley 1." Determine the difference ($m - M$) between the two lines you have drawn in four places. Use $\log P$ values of 0.2, 0.7, 1.2, 1.7 for this determination. Record each of these values in a table and obtain the average. Use this average as the distance modulus ($m - M$) to calculate the distance to the SMC. The formula is in your magnitude handout.

Table II. Shapley's Data for Halo Cepheids

$\log P$	M_V	$\log P$	M_V
0.0	-0.4	+1.0	-2.9
+0.2	-0.8	+1.2	-3.6
+0.4	-1.2	+1.4	-4.4
+0.6	-1.6	+1.6	-5.1
+0.8	-2.2	+1.8	-5.8

For many years, the distance scale of the universe was based on Shapley's calibration. However, as technology advanced and observational techniques improved, the need for revision of Shapley's calibration became apparent. Astronomy at first did not know about stellar populations and type I Cepheids (with 2% metallicity) and Type II Cepheids (with low metallicity).

5 Baade's Correction

Walter Baade, using the newly built Palomar 200 inch telescope, discovered that stars can be classified into two general age categories. Population I stars are relatively young and formed after the interstellar medium was enriched with metals from the explosions of supernova and the deaths of other stars. Our Sun is a population I star. Population II stars formed early in the history of the galaxy when there were few heavy elements because the Universe was young. When Baade observed the Andromeda galaxy he was only able to photograph Population I stars and the brightest of the Population II stars. Fainter Population II stars were not visible. This suggested to Baade that Population II stars are, in general, intrinsically 1.5 magnitudes fainter than Population I stars.

Since he could find no Cepheids in M31's globular clusters but many in the spiral arms, he deduced that the Cepheids in globular clusters must be Population II while the Cepheids in the spiral arms were Population I. Along with this came the realization that the globular cluster stars used by Shapley in his calibration must be about 1.5 magnitudes fainter than the spiral arm Cepheids observed by Leavitt. That is, because Shapley based his scale on intrinsically fainter Population II stars, his scale needed to be adjusted to accommodate the intrinsically brighter Population I stars studied by Leavitt. Obtain a new distance to the SMC by adding 1.5 magnitudes to your value of the distance modulus. Now calculate the revised distance to the SMC. How would the presence of interstellar dust affect the distance modulus and the distance you obtained?

Complete your new estimate of distance and prepare you report with title page, data reduction, data plot and calculation.