# Cepheid Variables

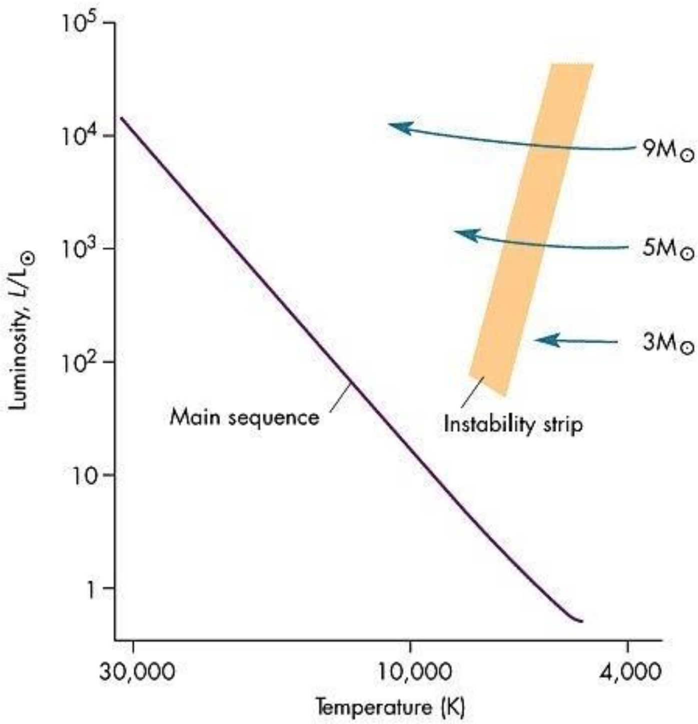


## Objectives

Measure periods of Cepheid Variable stars. Measure distances to galaxies.

## Introduction

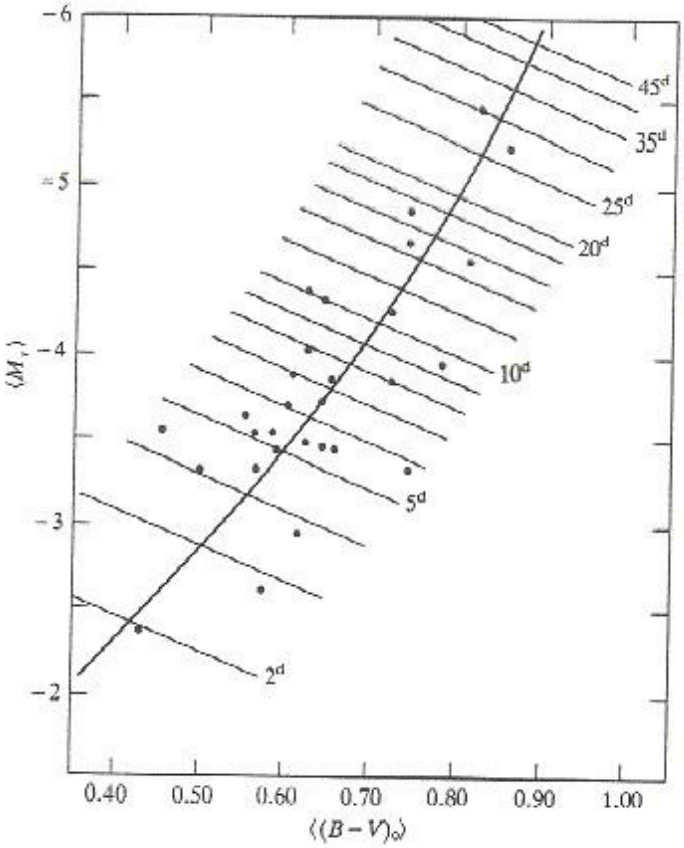
Massive stars of a certain age become unstable, and pass through a region in the HR diagram called the instability strip.




While stars are evolving through the instability strip they cannot attain a balance of forces, much like a flag waving in the wind. They pulsate regularly, periodically changing in brightness, size and color.

The cepheid variables are a class of variable stars inhabiting the instability strip, with delta Cepheii the type specimen. They are quite rare, since evolution through the instability strip is rapid. Cepheids pulsate with periods between about one and one hundred days. The periods are extremely precise, as good as the period of rotation of the Earth. They are distinguished from other variable stars by the shape of their light curves, which rise quickly and fall slowly.

Cepheid variables are very important to astronomers, because they exhibit a helpful property: their average brightness increases with the pulsation period. Here is a closeup view of the instability strip, showing pulsation periods in days. (In this HR diagram, luminosity and temperature have been replaced with absolute magnitude and color index.)




This diagram indicates that for cepheid variables, there is a relationship between absolute magnitude, color and period. Since the instability strip is narrow, it is possible to make an approximate relationship between period and luminosity alone, although some scatter is inevitable.

The cepheid variable period-luminosity relationship was first shown by Miss Henrietta Leavitt (1868-1921). Working at the Harvard Observatory, she determined the apparent magnitudes and periods for 25 cepheid variables in the Large and Small Magellanic Clouds. Since the Magellanic Clouds are each a nearby galaxy, the cepheids within each cloud are at essentially the same distance from the Earth. It seemed therefore that a relationship existed between the period of the cepheid and its absolute magnitude.

Calibration of the relationship between absolute magnitude and cepheid period has been done by finding the distance to cepheids within our galaxy, and by other means, none of which are completely satisfactory. Calibration uncertainties have been decreasing over the years, and this trend will no doubt continue. A straight-line relationship is found between absolute magnitude and the logarithm of the period. Here is an example:

$$M_V = -2.76 \log(P) - 1.40$$

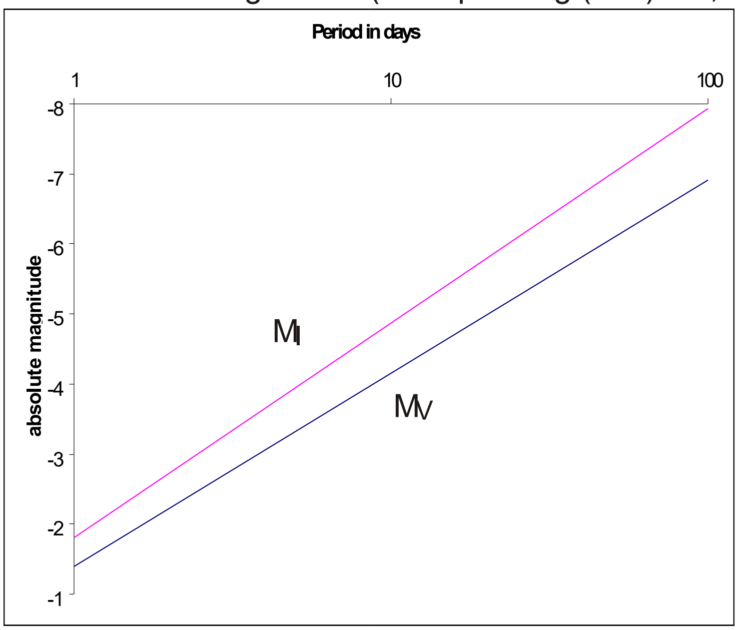
$$M_I = -3.06 \log(P) - 1.81$$ where

$M_V$ is the visual absolute magnitude

$M_I$ is the infra-red absolute magnitude

P is the period in days

Log is the common base 10 logarithm. (example: Log (100) = 2, $10^2 = 100$)

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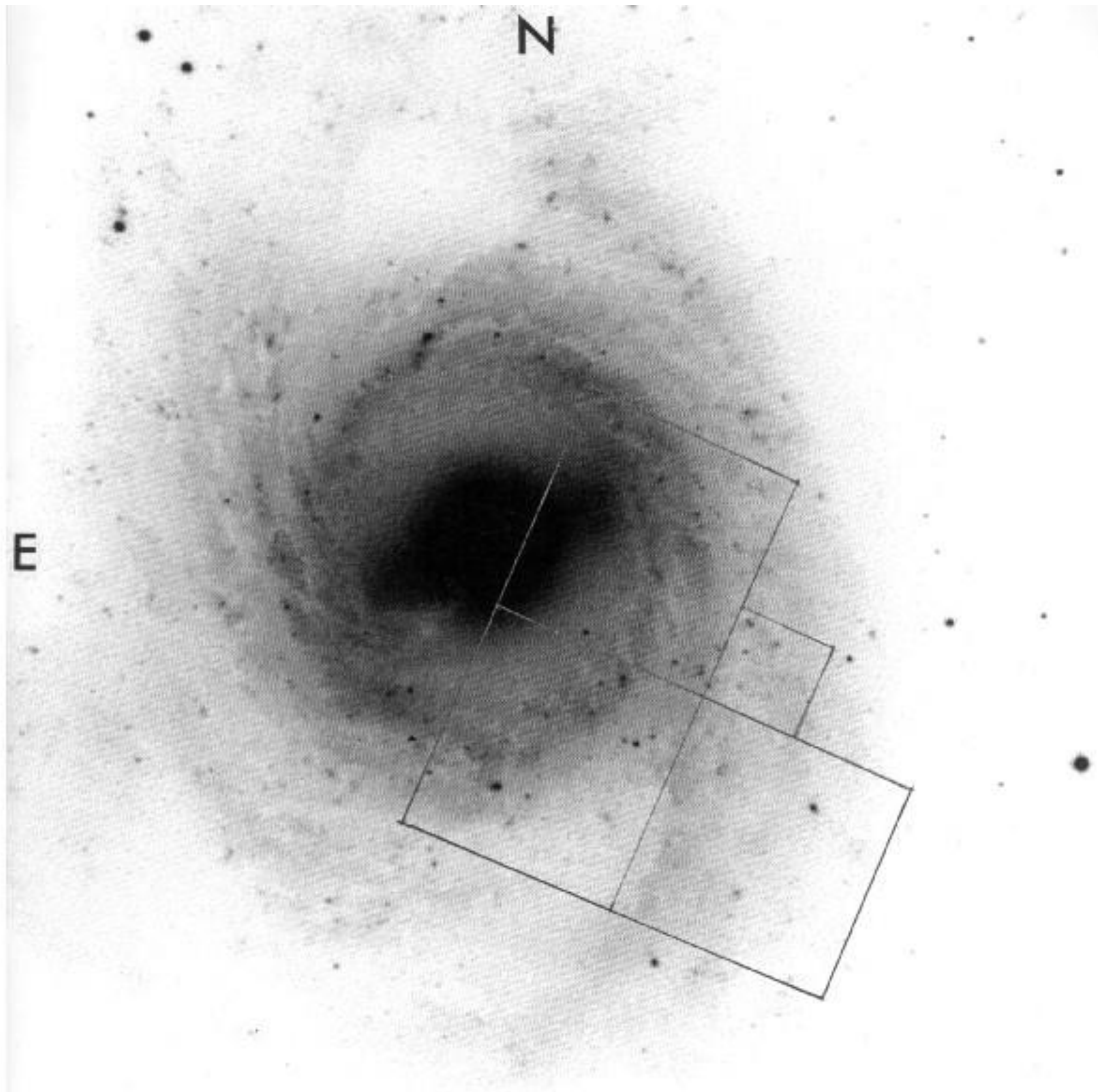
Since we have a calibration, we can measure the period of a cepheid variable star and find its absolute magnitude, which together with its apparent magnitude (averaged over the period) enables us to find the distance of the star.

$$\text{distance modulus} = m - M = 5 \log(D) - 5$$

where
m = the apparent magnitude
M = the absolute magnitude (the apparent magnitude if the star was 10 parsecs away) D
D= the distance in parsecs

## How it's done:

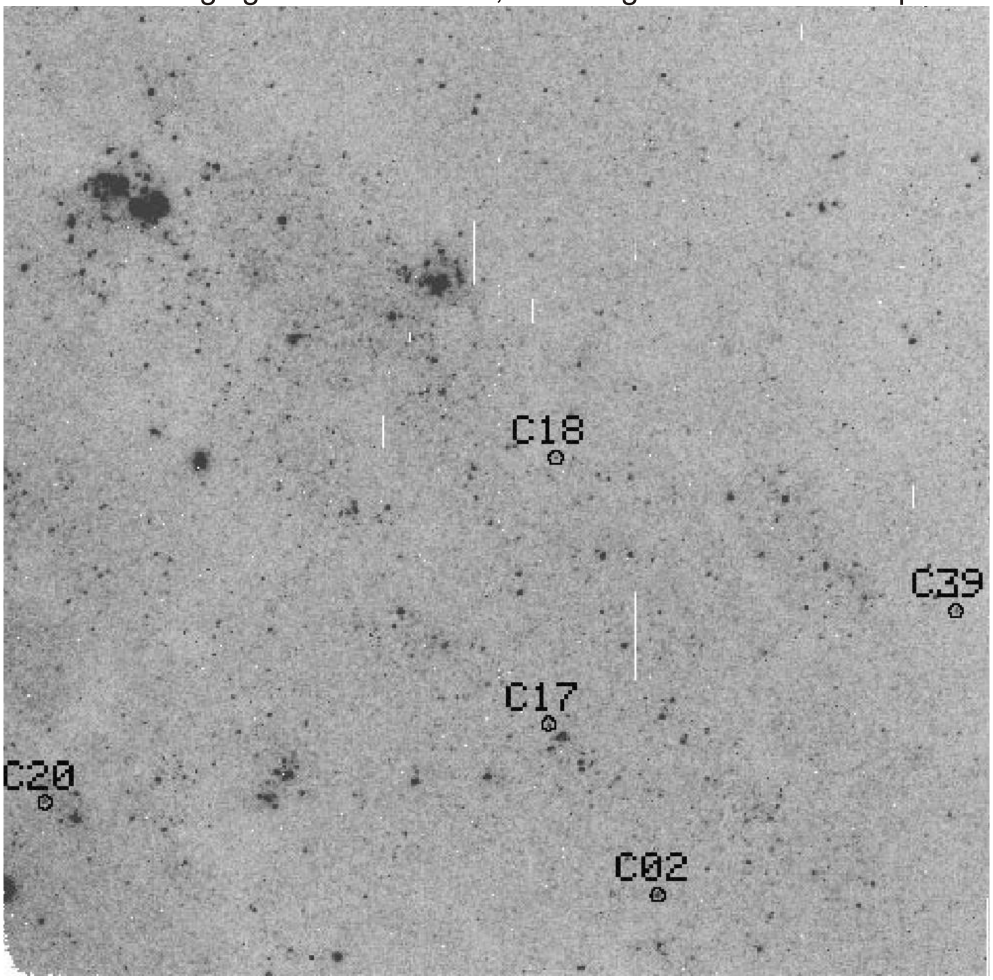
We start with a large-scale photo of NGC3351, a galaxy in the Leo group that is seen more or less face-on. We choose some fields to study with the Hubble Space Telescope.



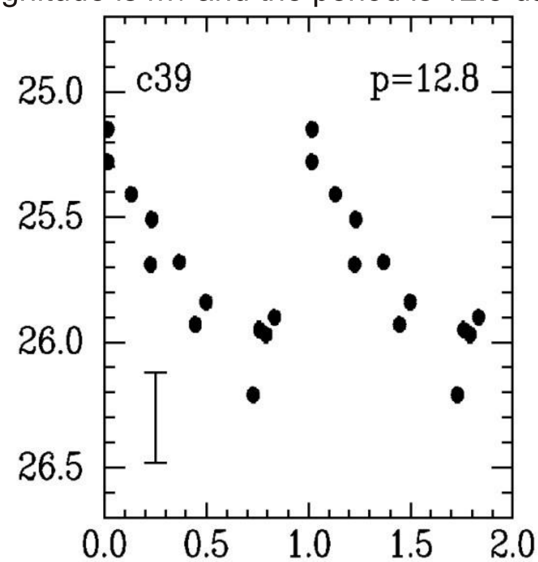

This is a distant galaxy, which means that the stars are both faint and close together as seen from Earth. We require both light-gathering power and high resolution. Doing this type of work was one of the main arguments for putting a telescope in space.

Cepheid variables are relatively rare, probably because they represent such a small fraction of an individual star's lifetime. Therefore, the search area is a large part of the galaxy. The search criteria are variability with a period between 1 and 100 days, with a light curve displaying a fast rise in brightness, followed by a slow decrease.

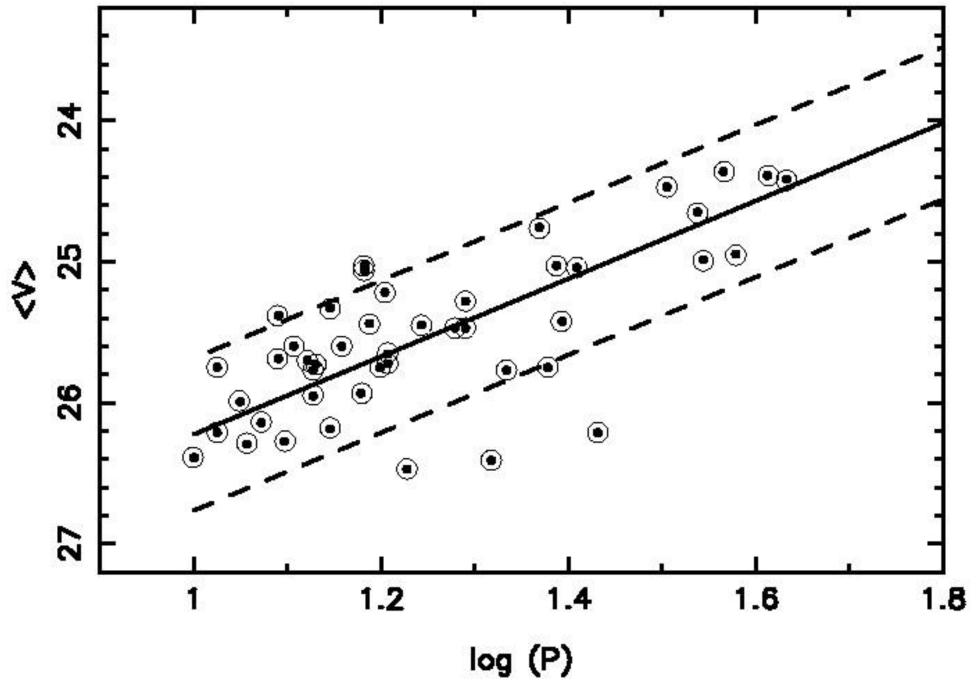
Some of the cepheid variables found in NGC3351 are shown below. Several defects in the CCD imaging device are seen, including some columns of pixels.




The light curve for the cepheid labeled C39 is shown below, plotted as two complete cycles. The magnitude is $m_V$ and the period is 12.8 days.



After getting data for a lot of cepheids, a plot of magnitude vs. the log of the period is prepared. The $m_V$ plot is shown here.




The central line is the calibration line. The dotted lines reflect the width of the instability strip. The equation for the central line is found to be

$$m_V = -2.76 \text{ Log } (P) + 28.98$$

From page 3, the calibration curve is

$$M_V = -2.76 \text{ Log } (P) - 1.40$$

Subtracting the second equation from the first, we obtain a distance modulus

$$(m - M) = 30.38$$

The analogous infra-red (I) magnitudes give (m - M) = 30.23.

These numbers are now tinkered a bit, including an allowance for interstellar reddening. The final distance modulus is given as (m - M) = 30.01 ± 0.19, corresponding to a distance of 10.0 ± 0.88 MPc (MPc is mega-parsec). This conversion is made using the formula on the bottom of page 3, rearranged to

$$D = 10^{0.2\,(m - M) + 1} = 10^{0.2(30.01) + 1} = 10^{7.002} = 1.005 \times 10^{7}$$

In this experiment, you will do all this (except for the tinkering and error analysis).

## Clock Arithmetic

Suppose you have an inaccurate wall clock, and you make a graph of the height of the tip of the minute hand above the floor as a function of time. You will get a curve (a sine wave) that repeats every hour, with a maximum height above the floor every hour. If you can monitor the clock continuously, it is very straightforward to find the period by finding the time it takes for the minute hand to make a full turn.

The period of a cepheid variable can't be found by this method, because of the amount of telescope time involved. The practical alternative is to make occasional observations, spread over many cycles. The observations are combined by guessing a period, and subtracting an integral number of periods from the time of each observation.

Here is a math example. Suppose the time an observation was made was 10.7256 days. Suppose the guessed period is 1.23 days.

$$\frac{10.7256}{1.23} = 8.72 = 8 + 0.72$$

We forget about the 8, and keep the 0.72, the fraction of the guessed period. The data point is plotted with the x axis value of 0.72.

If we guess the period correctly, all the observations can be combined to give a smooth curve. If we guess wrong, all the data points will not fall on a single curve, and we have to guess again. Since we are searching for a single smooth curve, measurement error will limit the accuracy of the period.

The left side of the plot on the bottom of page 5 was prepared in this way. The data is repeated on the right side, with no mathematical significance, but giving an important visual clue to the periodicity. Also, the final figure was shifted so as to place the maximum at the beginning.

## Program

The program that you will use is called CEPHEIDS.EXE, and there are several steps for you to do. You will work alone or with a partner according to directions from your instructor.

### Step 1

Type your name(s) in the box provided and click on the OK button. When you print out results, your name(s) will appear on the printout. If you are working with a partner, you will have to print twice.

### Step 2

Here you will measure periods by guessing a period and checking to see if you have a smooth function. The period is adjusted with a sliding control. Periods are between one and ten days. There are Coarse and Fine period adjustments, you can print your results when done.

From the second menu entry, marked Cepheid, choose selection(s) according to directions from your instructor. The entries are

| | | |
|---|---|---|
| a) | Sine wave | Not a star. A large number of closely spaced “observations” make this an easy place to start |
| b) | Noisy Sine wave | Not a star. The number of points is much fewer than in the first selection, and noise has been added to add realism. The period is chosen at random, so your results won’t agree with those of other students. |
| c) | Del-Cep | The obvious actual cepheid to start with. There are two data sets, $m_v$ and (b-v). The data for this star and the two stars below are from Varren Parker, Angelo State University. The period is between 5 and 6 days. |
| d) | Eta-Aql | There are many erroneous (b-v) data points that should be ignored. The period is between 7 and 8 days. |
| e) | SU-Cyg | The data are OK. The period is between 3 and 4 days. |

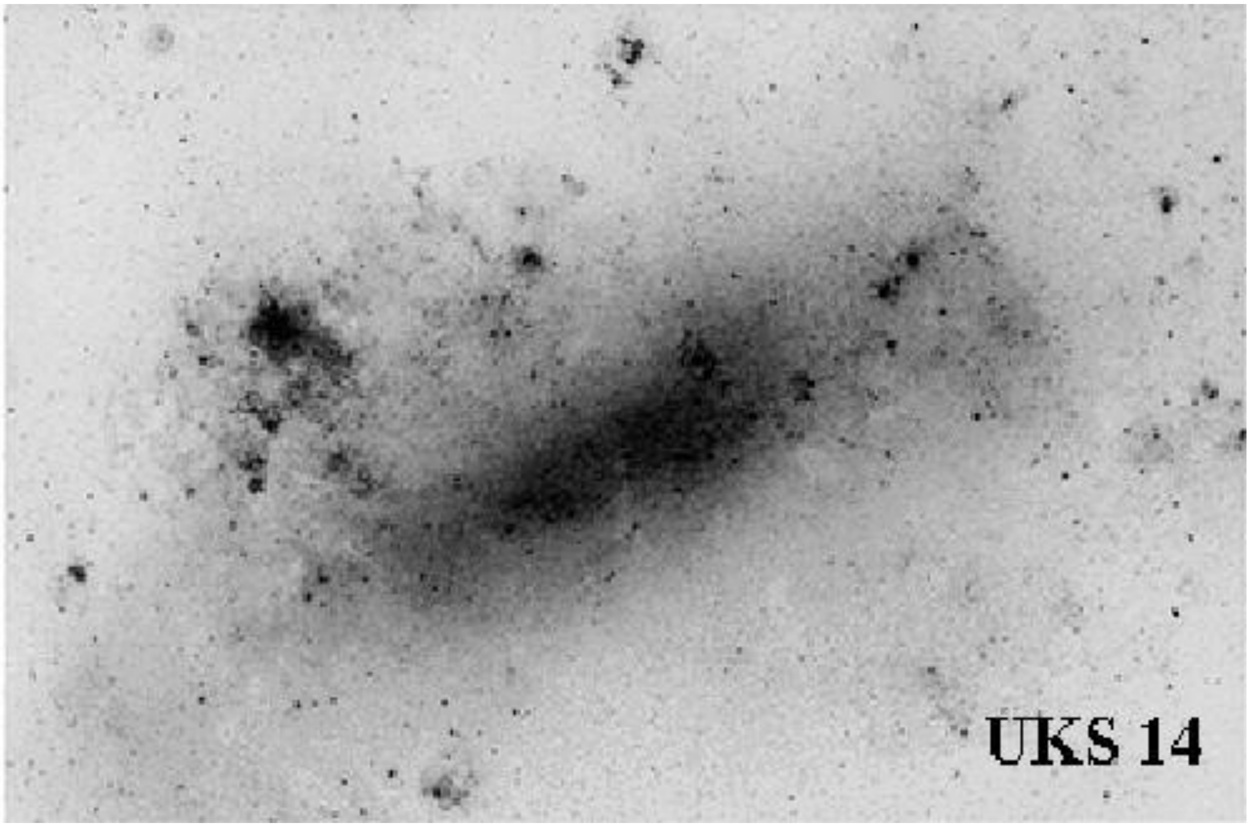
Step 3

Here you will measure the distance to a galaxy by matching observations of average apparent magnitudes and periods of cepheids with calibration lines that are shifted vertically with a sliding control. Color codes enable all of the data to be presented simultaneously (green for $m_v$, red for mr and gray for mi.

From the second menu entry, marked Galaxy, choose selection(s) according to directions from your instructor. The entries are the Large Magellanic Cloud (LMC) and M100.

## LMC Notes

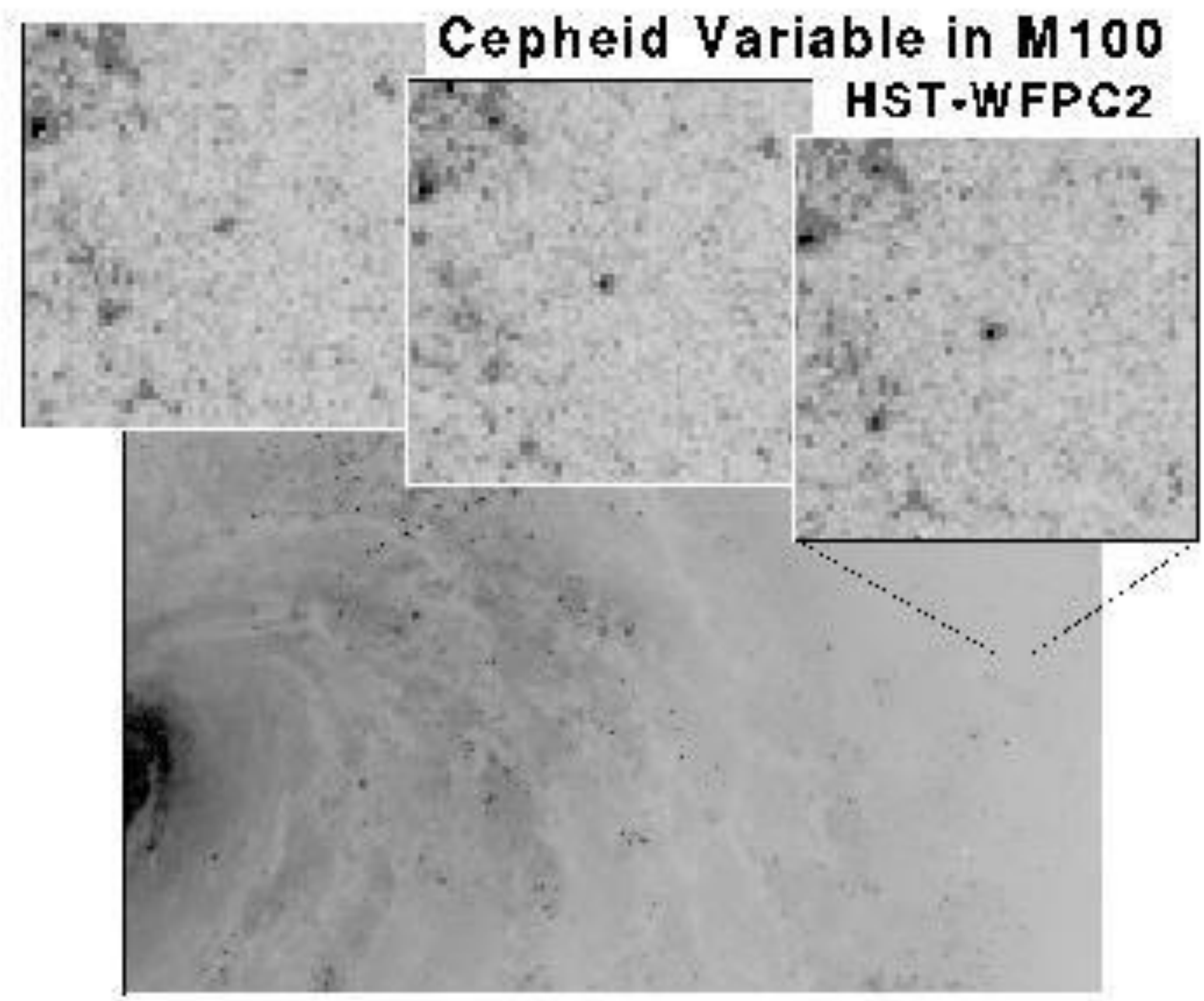
This is the Large Magellanic Cloud. The study of cepheids and the period-luminosity relationship started here. The LMC is a companion galaxy to the Milky Way, and is seen face-on.




The data that you will use is fairly recent (1999). It comes from the EROS-2 microlensing (MACHO) Project, which searched the central part of the LMC for gravitational lenses. The search didn't find many MACHO's (i.e. brown dwarfs), but it did find quite a few cepheids in the Small and Large Magellanic Clouds. A catalog of 177 LMC cepheids is of high quality, and that is your data set.

## M100 Notes

M100 is a large spiral galaxy seen face-on. It is near the center of the Virgo supercluster, which we may be a part of. It is even farther away than the galaxy shown on page 4. Finding cepheids in M100 was one of the important achievements of recent decades. Part of M100 is shown below. Insets are of a cepheid undergoing brightness changes.




The data set consists of a catalog of 52 cepheids, in two colors (V and I), with periods ranging from 10 to about 52 days. After doing this section of the experiment, answer the question on the data sheet.

## Data

Name ________________________________________ Date _____________________

| Star | Period |
|---|---|
| Sine wave | __________ days |
| Noisy sine wave | __________ days |
| Delta Cep | __________ days |
| Eta Aql | __________ days |
| SU Cyg | __________ days |

| Galaxy | Distance modulus | Distance (kpc) |
|---|---|---|
| LMC | __________ | __________ |
| M100 | __________ | __________ |

## Question

Why do you think the cepheid data for M100 doesn't extend to periods less than ten days? (Hint: look at the m scale)