Cepheid Variable Stars & Distance Determination

Some types of pulsating variable stars such as Cepheids exhibit a definite relationship between their period and their intrinsic luminosity. Such period-luminosity relationships are invaluable to astronomers as they are a vital method in calculating distances within and beyond our galaxy.

Discovery of the Period - Luminosity Relationship

Credit: AAVSO
Henrietta Leavitt

During the first decade of the 1900s Henrietta Leavitt (1868 - 1921), working at the Harvard College Observatory, studying photographic plates of the Large (LMC) and Small (SMC) Magellanic Clouds, compiled a list of 1,777 periodic variables. Eventually she classified 47 of these in the two clouds as Cepheid variables and noticed that those with longer periods were brighter than the shorter-period ones. She correctly inferred that as the stars were in the same distant clouds they were all at much the same relative distance from us. Any difference in apparent magnitude was therefore related to a difference in absolute magnitude. When she plotted her results for the two clouds she noted that they formed distinct relationships between brightness and period.

Her plot showed what is now known as the *period-luminosity relationship*; cepheids with longer periods are intrinsically more luminous than those with shorter periods.

The Danish astronomer, Ejnar Hertzsprung (1873-1967) quickly realised the significance of this discovery. By measuring the period of a Cepheid from its light curve, the distance to that Cepheid could be determined. He used his data on nearby Cepheids to calculate the distance to the Cepheids in the SMC as 37,000 light years away.

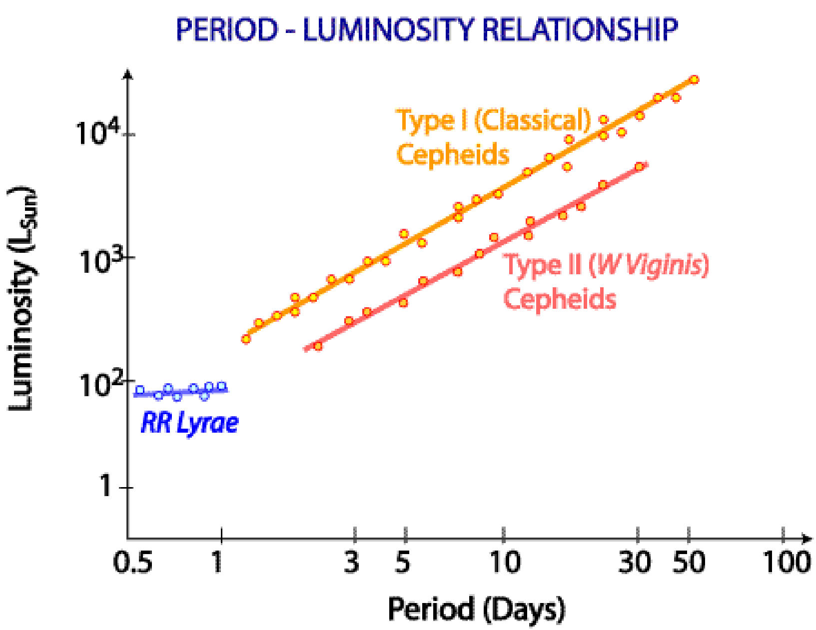
Credit: The Hale Observatories, courtesy AIP Emilio Segre Visual Archives
Edwin Hubble at the 100" Hooker Telescope on Mt Wilson

Harlow Shapley, an American astronomer using a larger number of Cepheids, recalibrated the absolute magnitude scale for Cepheids and revised the value of the distance to the SMC to 95,000 light years. He also studied Cepheids in 86 globular clusters and found that the few dozen brightest non-variable stars in each cluster was about 10 × brighter than the average Cepheid. From this he could infer the distance to globular cluster too distant to have visible Cepheids and realised that these clusters were all essentially the same size and luminosity. By mapping the distribution and distance of globular clusters he was able to deduce the size of our galaxy, the Milky Way.

In 1924 Edwin Hubble detected Cepheids in the Andromeda nebula, M31 and the Triangulum nebula M33. Using these he determined that their distances were 900,000 and 850,000 light years respectively. He thus established conclusively that these "spiral nebulae" were in fact other galaxies and not part of our Milky Way. This was a momentous discovery and dramatically expanded the scale of he known Universe. Hubble later went on to observe the redshift of galaxies and propose that this was due to their recession velocity, with more distant galaxies moving away at a higher speed than nearby ones. This relationship is now called *Hubble's Law* and is interpreted to mean that the Universe is expanding.

Calculating Distances Using Cepheids

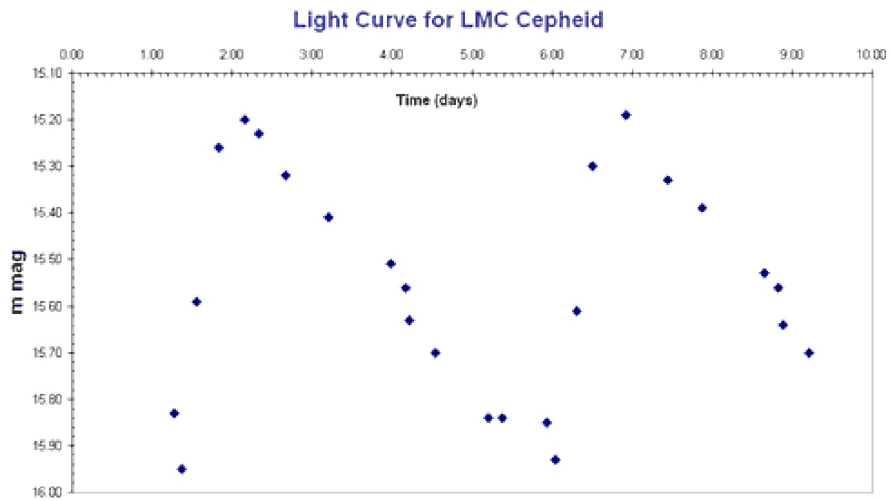
Both types of Cepheids and *RR Lyrae* stars all exhibit distinct period-luminosity relationships as shown below.



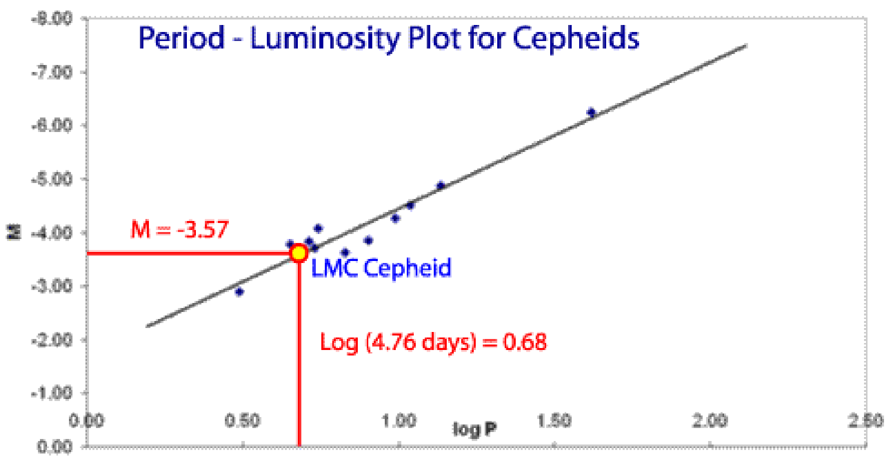
Period-luminosity relationship for Cepheids and RR Lyrae stars.

Let us now see how this relationship can be used to determine the distance to a Cepheid. For this procedure we will assume that we are dealing with a Type I, Classical Cepheid but the same method applies for *W Virginis* and *RR Lyrae*-type stars.

1. Photometric observations, be they naked-eye estimates, photographic plates, or photoelectric CCD images provide the apparent magnitude values for the Cepheid.
2. Plotting apparent magnitude values from observations at different times results in a light curve such as that below for a Cepheid in the LMC.



3. From the light curve and the photometric data, two values can be determined; the average apparent magnitude, *m*, of the star and its period in days. In the example above the Cepheid has a mean apparent magnitude of 15.56 and a period of 4.76 days.
4. Knowing the period of the Cepheid we can now determine its mean absolute magnitude, *M*, by interpolating on the period-luminosity plot. The one shown below is based on Cepheids within the Milky Way. The vertical axis shows absolute magnitude whilst period is displayed as a log value on the horizontal axes.



The log of 4.76 days = 0.68. When this is plotted a value of about -3.6 results for absolute magnitude.

5. Once both apparent magnitude, *m*, and absolute magnitude, *M* are known we can simply substitute in to the distance-modulus formula (4.2) and rework it to give a value for *d*, the distance to the Cepheid.

   $m - M = 5 \log(d/10)$ (4.2)
   as you should recall, this can be rewritten as:

   $d = 10^{(m - M + 5)/5}$
   now substituting in:

   $d = 10^{(15.57 - (-3.6) + 5)/5}$
   $d = 10^{24.17/5}$
   $d = 10^{4.834}$
   ***d* = 68,230 parsecs**
   This means that the Cepheid in the LMC is about 68.2 kpc (or about 222,000 light years away). More importantly, if we infer that the size of the LMC relative to its distance from us is small we have also found the distance to the LMC within which the Cepheid is located.

6. In practice astronomers would try and observe as many Cepheids as possible in another galaxy in order to determine a more accurate distance. As the number of stars observed go up the uncertainties involved in calculations for individual stars can be statistically reduced.

The basic steps, therefore for distance calculation using pulsating variables are straightforward though the detail makes it harder in practice.

Standard Candles

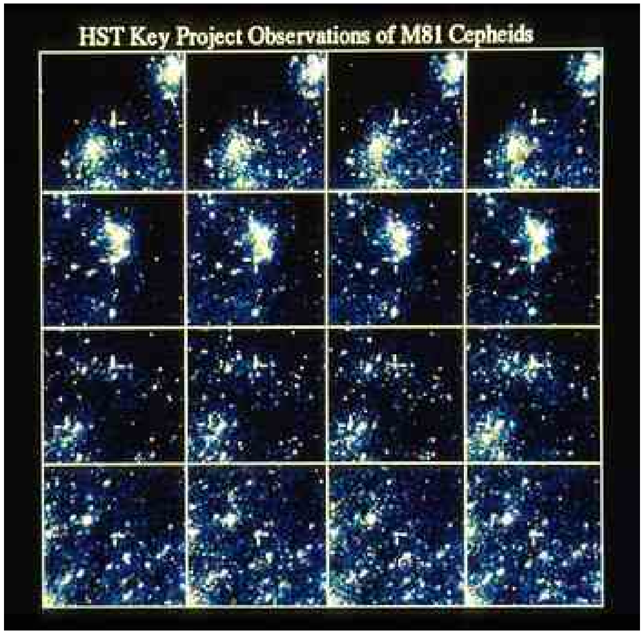
The term standard candle applies to celestial objects with well-defined absolute magnitudes which are assumed to not vary with age or distance. Type I and II Cepheids and *RR Lyraes* are all examples. All Cepheids with a certain period are assumed to have the same absolute magnitude. Measuring the apparent magnitude of a Cepheid then allows us to determine its distance using the period-luminosity relationship. If two Cepheids have the same period but is fainter than the other it must be further away. RR Lyraes similarly can be used as standard candles although as their intrinsic luminosity is lower than Classical Cepheids they cannot be detected at the great distances of Cepheids.

Type Ia supernovae may be approximated to standard candles as their absolute magnitude reaches about -19 at maximum brightness. Given their extreme luminosity they can be used to probe much further out into the Universe than Cepheids. Two recent projects, the Supernova Cosmology Project and the High-Z SN Search have both observed dozens of supernovae in distant galaxies to try and determine H and the geometry of the Universe. Both teams independently arrived at the the conclusion that not only is our Universe expanding but it is actually accelerating, a result that the prestigious American magazine *Science* announced was the research advance of 1998.

The Hubble Key Project

The US$2 billion Hubble Space telescope was built and launched in 1990 to conduct observations not then achievable using ground-based telescopes. One of its major initial observational programs, dubbed the Hubble Key Project, was aimed at refining and calibrating the extragalactic distance scale by observing Cepheids in other galaxies. The goal was to use the recalibrated scale to calculate a more precise value for the Hubble Constant, H_0 which at that time was measured as somewhere between 50 and 100 km s^{-1} Mpc^{-1} (kilometres per second per megaparsec) depending on the method used.

The international team of astronomers discovered many new cepheids in the 18 galaxies they studied. In the giant spiral M81, for instance they found 32 Cepheids to add to only two that had been found previously using ground-based telescopes. Using the HST they made 22 twenty-minute exposures of each of two fields in M 81containing the Cepheids. Once the data from these was reduced they were able to calculate a distance to M 81 of 3.4 megaparsecs (about 11 million light years) compared to the previous range of values of 1.3 to 5.6 megaparsecs.



Credit: *NASA*, *STScI*
HST images of Cepheids in M 81. Each row shows four successive views of part of the field containing a Cepheid marked with dashes.

The final results of the Key project, published in 2001 gave a value of H_0 = 72+/-8 km s^{-1} Mpc^{-1}. This value was based on the results of the Cepheid studies which were then combined with other techniques such as observations of Type Ia supernovae, Type II supernovae, the Tully-Fisher relation and the surface brightness of galaxies. The uncertainty of the value was close to the original +/- 10% target for the project.

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