STANDARD CANDLES

RONALD E. MICKLE
Denver, Colorado 80005

ABSTRACT

To an astronomer, determining the size and shape of our Milky Way Galaxy, or the distance to other galaxies, was as compelling as determining the shape and size of our world was to early explorers. So astronomers developed methods that use certain celestial objects, including galaxies and their HII regions, supernovae and individual stars to measure astronomical distances. These objects are referred to as standard candles [Kaufmann & Freedman 1999].

The classes of stars used as standard candles include Cepheids, RR Lyrae and Type Ia supernovae. We will explore and discuss how Cepheids are used as tools to measure distances, including how they were used to determine the size and shape of the Milky Way Galaxy, and in determining distances to other galaxies. We will also review the history of the Cepheids, their behaviour and what impact all this had on astronomy.

1. WHAT IS A STANDARD CANDLE?

To help understand what is meant by standard candle, we first need to have a basic understanding of how distances are measured in astronomy. For small distances such as from the earth to the moon, lasers are used. Moving further out to Mercury, Venus or Mars, we use radar. Leaving our solar system and measuring to nearby stars, we use semi-annual parallax. And out to 500 parsecs (pc), spacecraft (e.g. Hipparcos) are used with measurements computed trigonometrically. We refer to these as direct methods of measurement.

At distances greater than 500 pc, the error in the parallax measurement is too great and not usable. Indirect methods are used based on stellar properties such as luminosity, radii, the effective temperature and others. Distances are determined from relationships connecting these properties, including the period-luminosity relation for Cepheid variables. [Illingworth & Clark 2000]

While it is difficult to find a 'pure' definition for STANDARD CANDLE, reliable sources provide enough information to define it as saying there is no single object used for a Standard Candle; there are collections of stellar objects with known luminosities that allow them to be used to determine distances. The Standard Candle object used depends on the distance being measured. The brightest Cepheids, for example, can be seen out to about 60 megaparsecs (Mpc). For distances of 150 and 250 Mpc, red and blue supergiants can be used, respectively. For distances even greater, a galaxy's HII region or brightness of its globular clusters are used. Beyond 900 Mpc, astronomers rely on supernovae. In all measurements, as the distance increases, the accuracy decreases. [Kaufmann & Freedman 1999, Illingworth & Clark 2000]

2. *CEPHEIDS*: FROM DISCOVERY TO COMPREHENSION

In the late 18th century amateur astronomer John Goodricke discovered that the star δ Cephei reached its brightest and dimmest point over a period of 5.4 days and had a magnitude variation 2.3. Goodricke had unknowingly identified THE prototypical class of star that would be referred to as Cepheids and they would play a crucial role in astronomy for the next several centuries. Cepheids would serve as the cornerstone in determining the size and shape of the Galaxy and determining distances to other galaxies, which at the time were referred to as spiral nebulae and thought to lie within the Milky Way.

During the same period, English astronomer William Herschel was attempting to establish the size and shape of the Galaxy, as were other astronomers. Over 100 years after Goodricke discovered the variability of δ Cephei, Russian astronomer Aristarkh Belopol'skii revealed that δ Cephei's spectral lines shifted back and forth with its period.

By the early 1900's, astronomers were still trying to ascertain the physical size of the Galaxy. Dutch astronomer Jacobus Kapteyn incorrectly concluded, like Herschel, that the sun was at the centre of the Galaxy, but did add another dimension by determining the Milky Way was 55,000 light years in diameter.

In 1904, while working for the Harvard College Observatory, Henrietta Leavitt measured the magnitude of 59 variables and the periods of 25 using photographs of the Small Magellanic Cloud (SMC). During her research, Leavitt noticed that the brighter the variable, the longer the period (Table 1). She also noted that these variables were similar to variables she had observed in globular clusters. The relationship between the variable's period and its apparent brightness would later be referred to as its period-luminosity (P-L) relation.[Pickering 1912] The P-L relation is defined by not a single star, but an ensemble of stars; each one obeys it.

TABLE I.

PERIODS OF VARIABLE STARS IN THE SMALL MAGELLANIC CLOUD.

H.	Max.	Min.	Epoch.	Period.	Res. *M.*	Res. *m.*	H.	Max.	Min.	Epoch.	Period.	Res. *M.*	Res. *m.*
			d.	d.						d.	d.		
1505	14.8	16.1	0.02	1.25336	−0.6	−0.5	1400	14.1	14.8	4.0	6.650	+0.2	−0.3
1436	14.8	16.4	0.02	1.6637	−0.3	+0.1	*1355*	14.0	14.8	4.8	7.483	+0.2	−0.2
1446	14.8	16.4	1.38	1.7620	−0.3	+0.1	1374	13.9	15.2	6.0	8.397	+0.2	−0.3
1506	15.1	16.3	1.08	1.87502	+0.1	+0.1	818	13.6	14.7	4.0	10.336	0.0	0.0
1413	14.7	15.6	0.35	2.17352	−0.2	−0.5	*1610*	13.4	14.6	11.0	11.645	0.0	0.0
1460	14.4	15.7	0.00	2.913	−0.3	−0.1	*1365*	13.8	14.8	9.6	12.417	+0.4	+0.2
1422	14.7	15.9	0.6	3.501	+0.2	+0.2	*1351*	13.4	14.4	4.0	13.08	+0.1	−0.1
842	14.6	16.1	2.61	4.2897	+0.3	+0.6	827	13.4	14.3	11.6	13.47	+0.1	−0.2
1425	14.3	15.3	2.8	4.547	0.0	−0.1	*822*	13.0	14.6	13.0	16.75	−0.1	+0.3
1742	14.3	15.5	0.95	4.9866	+0.1	+0.2	823	12.2	14.1	2.9	31.94	−0.3	+0.4
1646	14.4	15.4	4.30	5.311	+0.3	+0.1	824	11.4	12.8	4.	65.8	−0.4	−0.2
1649	14.3	15.2	5.05	5.323	+0.2	−0.1	821	11.2	12.1	97.	127.0	−0.1	−0.4
1492	13.8	14.8	0.6	6.2926	−0.2	−0.4							

HARVARD COLLEGE OBSERVATORY, Circular 173. Leavitt listed 25 (Cepheid) variables arranged in order of their period.

Note that in Figure 1 the period of the variables is along the x-axis and measured in days, while in Figure 2 the x-axis is equal to the logarithm of the period. Also note in Fig.2, 22 of the 25 variables have P ≤ 16 days ($10^{1.2}$). The graphs clearly show the relation between the minima and maxima brightness to the period [Pickering 1912]. Today, we know of approximately 204 Cepheids in the Large Magellanic Cloud (LMC) and 132 in the SMC [Pietrzynski and Udalski 1999].

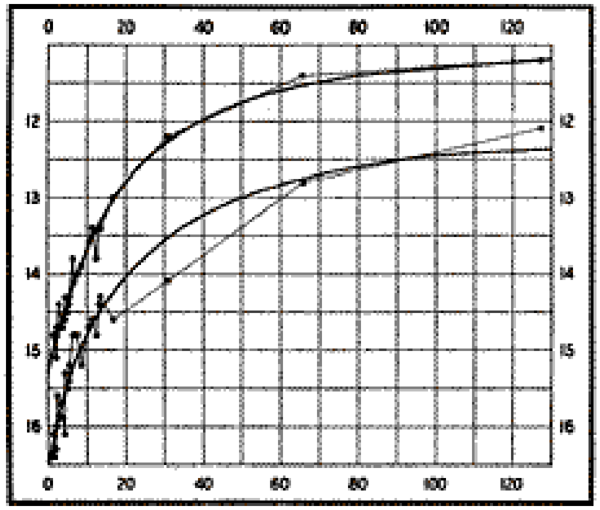

Fig. 1.

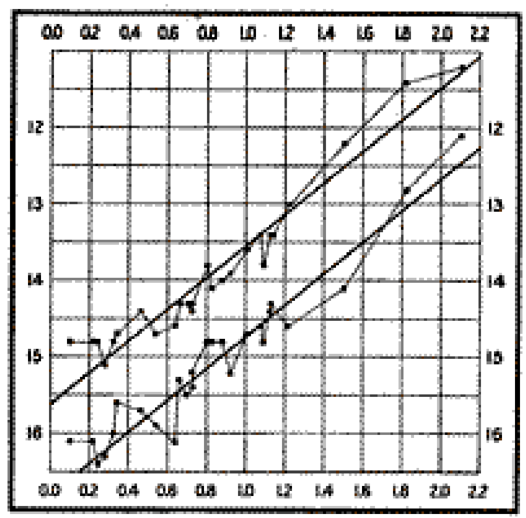

Fig. 2.

HARVARD COLLEGE OBSERVATORY, Circular 173. Leavitt's graph of the 25 (Cepheid) variables she listed in Table1 showing the relationship in maximum/minimum brightness and their periods.

In 1913, about a year after Leavitt's paper was published, Danish astronomer Ejnar Hertzsprung realized that if the P-L relation could be calibrated, the absolute magnitude could be determined from their periods. Leavitt had already noted the strong parallel in her variables from the SMC and the variables in globular clusters, and Hertzsprung noted their likeness with δ Cephei. His later attempt to calibrate the P-L relation using the SMC was unsuccessful. [Pickering 1912]

British astronomer Arthur Eddington conducted further studies of δ Cephei in 1918, as did American astronomer John Cox in the 1960's, concluding the magnitude variations were the result of the expansion and contraction of the star's outer envelope and that helium was the engine for the pulsations. As the variable contracts, the temperature increases resulting in an increase in apparent brightness. As the variable expands the temperature decreases and the star fades. [Kaufmann & Freedman 1999]

While the discoveries made by Goodricke, Belopol'skii, Eddington and Cox were important, the studies conducted by Leavitt set the foundation for future studies in determining galactic distances.

Meanwhile, the dimension of the Galaxy was still in question. During 1918-20, Harlow Shapley of the Mount Wilson Observatory was studying 93 globular clusters in an attempt to deduce the size and shape of the Milky Way. It was during this time he improved upon Hertzsprung's calibration and revised the magnitudes of Leavitt's photographic plates. Shapley's P-L plot used stars from seven stellar systems. Shapley concluded in his studies that the distribution of the clusters was spherical around a central point in the area of the sky around the constellation Sagittarius and correctly surmised the clusters were gravitationally bound to the centre of the Milky Way. [Allen 2001]

Keep in mind that disagreements continued in the astronomical community regarding the location of the 'spiral nebulae' being observed. As mentioned earlier, some astronomers believed these nebulae to lie within the Milky Way while others, such as Heber Curtis of the Lick Observatory believed them to be island universes apart from the Milky Way, containing large collections of stars. [Kaufmann & Freedman 1999]

These disagreements eventually led to the Shapley-Curtis Debate of 1920 at the National Academy of Sciences in Washington, D.C. While Shapley successfully demonstrated that our Galaxy was a star system by using use of globular clusters to identify the centre of the Milky Way, Curtis correctly argued that our Universe contained many galaxies and that spiral nebulae thought to be part of the Milky Way were indeed other galaxies. [Encyclopaedia of Astronomy and Astrophysics, Great Debates in Astronomy]

Then in 1922-24, while working at the Mt. Wilson Observatory, Edwin Hubble found that certain spiral nebula contained Cepheid variables. He knew, based on groundwork conducted by Leavitt and Shapley, that there was a correlation in the period and absolute magnitude. Using the relationship between distance and magnitude, Hubble was able to show that the Cepheids within the spiral nebulae were in fact hundreds of thousands of light-years away, outside our Galaxy. Hubble announced his discovery in December 1924 at a meeting of the American Astronomical Society. The impact on astronomy was enormous. It provided astronomers the basic tools by which to measure the distance to other galaxies and determine the size and shape of our Galaxy. [Kaufmann & Freedman 1999, STScI, Encyclopaedia Britannica 1996]

3. WHY *CEPHEIDS* CAN BE USED AS STANDARD CANDLES?

Of approximately 88[b] types of intrinsic variable stars, 34 are pulsating variables of which Cepheids are but one class [Encyclopaedia of Astronomy and Astrophysics]. Cepheids have two properties that make them useful as standard candles for measuring distances. First, they are very luminous, making them visible at distances measured in the millions of parsecs. Second, as mentioned earlier, a Cepheid's period is directly related to its luminosity and is referred to as the period-luminosity (P-L) relation. [Kaufmann & Freedman 1999]

We discussed previously that the use of Cepheids as a standard candle is in large part due to the work by Leavitt in the early 1900's and her understanding there was an implied relation between period and absolute magnitude [Ryder 2005]. But in the early part of the 20th century there was no direct method by which to calibrate the period-luminosity relation. [Europe Education Program]

For Cepheids to be used as standard candles, they must be calibrated. By calibrating, a previously measured distance is used to step up to the next further distance, as in climbing a ladder. The Distance Ladder is a scale illustrating different methods to measure distances, each method being a 'rung' of that ladder (Fig. 3). We must also identify which of the two types Cepheid we are working with, Type I or II. Type I (Population I) Cepheids have a high metallicity and Type II a low metallicity. Type II are also less luminous than Type I [Illingworth & Clark 2000].

We'll start with the closer of the Cepheids, Type II. They are older, less luminous than Type I and can be found in globular clusters and the galactic halo. Since the distance to

[b] Wilson states 88 types of intrinsic variables, but the list he provides totals 78.

globulars has already been determined by using RR Lyrae stars, we can calibrate the Cepheids using RR Lyraes in the cluster. However, the brightest Cepheids can be seen 100 times further than RR Lyraes, hence the limitation of RR Lyraes.

Type I Cepheids are not found in open clusters, therefore, RR Lyraes can not be used for their calibration. Instead, we calibrate Type I Cepheids using the moving cluster parallax or Main-sequence fitting. [Liverpool John Moores University]

Today, astronomers have calibrated for each of the Magellanic Clouds and produced plots for the P, absolute magnitude (M) and L [Ryder 2005]. In applying the P-M relation to Cepheids, the astronomer determines the period and apparent magnitude (m), refers to the P-M graph and locates P. Using the distance modulus m-M, the distance (d) is determined.

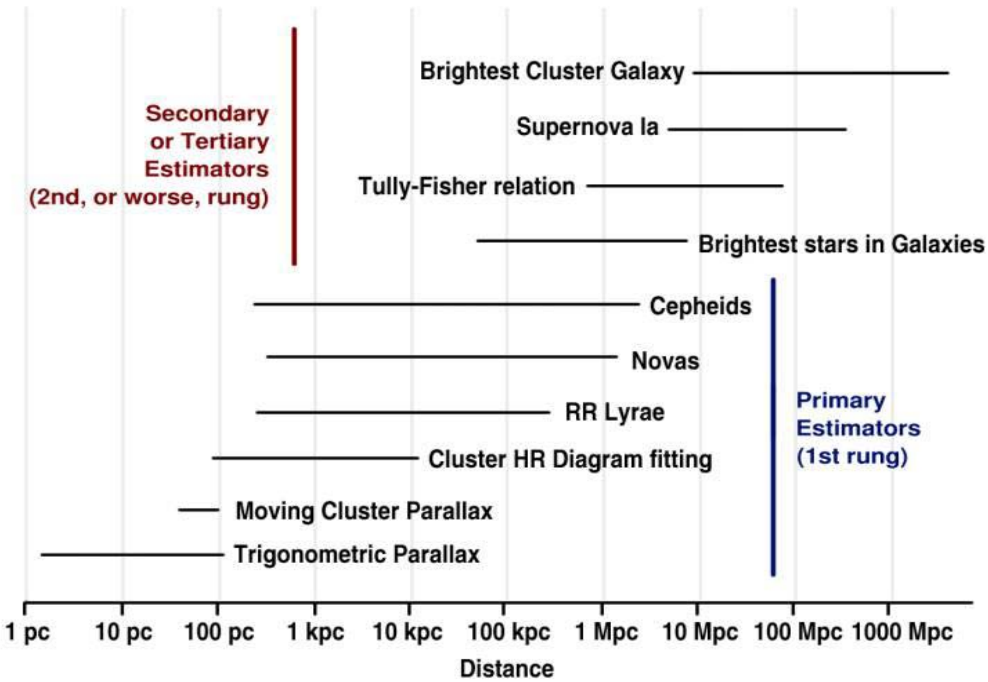

Figure 3
The Distance Ladder; Liverpool John Moores University

4. CONCLUSION

I found it difficult to keep this paper within the 2000 word limit, due to the large volume of information available on the subject. Remarkably, Edwin Hubble accomplished what others had been attempting for decades – he was able to apply the P-L relation accurately enough to show that spiral nebula were located beyond our Galaxy! So, even though some of Hubble's measurements fell short by as much as 50% [Allen 2001], he still took the astronomical community from intergalactic to extragalactic. However, I believe that the work by Leavitt in identifying the relationship between a Cepheid's period and its luminosity was as paramount to moving astronomy forward in determining distances as was Hubble's discovery.

In the 220 years since the first Cepheids were recognized, astronomy has made great progress in utilizing their unique characteristics as standard candles for measuring large distances. Our methods continue to be refined and recalibrated, increasing accuracy.

During the 1950's, astronomers attempted to add a colour (C) index to better refine the P-L relation and increase accuracy, but this led to confusion when colour was used interchangeably with temperature.

The debate revolving around the calibration of the P-L or the PLC relation continues, but these calibrations seem almost insignificant. Advances in instrumentation and telescopes have allowed astronomers to measure, with some degree of accuracy, the distances to the very edge of the known universe.

As quoted in Allen's [Allen 2001] dissertation, "We will leave the final cautionary note to Fernie (1969). He recalls Hubble's remarks on the Cepheid scale at a lecture in 1935 before Baade's great correction:

> "Further revision is expected to be of minor importance."

5. REFERENCES

Kaufmann & Freedman 1999, *Universe*, Fifth Edition, p. 640-41, 649.
Illingworth & Clark 2000, *The Facts on File Dictionary of Astronomy*, Fourth Edition.
Pickering, E March 3, 1912, Harvard College Observatory, Circular 173.
Pietrzynski and Udalski 1999, Acta Astron., 49, 543.
Allen, N.J. *The Cepheid Distance Scale: A History* 2001, AGSM BA BEd MSc FRAS MInstPI.
Encyclopaedia of Astronomy and Astrophysics, access through Swinburne University, Center for Astrophysics & Supercomputing.

- Wilson, R. October 2001, *Variable Stars,* http://eaa.iop.org/full/eaa-pdf/eaa/1893.html.
- Karovska & Sasselov November 2000, *Stellar Diameters,* http://eaa.iop.org/full/eaa-pdf/eaa/1874.html.
- Milky Way Galaxy, Published: April 2002, http://eaa.iop.org/full/eaa-pdf/eaa/4700.html.
- Shapley, Harlow (1885–1972), Published: November 2000, http://eaa.iop.org/index.cfm?action=search.home&quick=1&field1=&query1=shapley-harlow&newsearch=1&coll=ft.
- Curtis, Heber Doust (1872–1942), Published: November 2000, http://eaa.iop.org/full/eaa-pdf/eaa/3556.html.

Great Debates in Astronomy, *The Scale of the Universe (1920)*, http://antwrp.gsfc.nasa.gov/diamond_jubilee/debate.html.
STScI, Space Telescope Science Institute, http://www.phys-astro.sonoma.edu/BruceMedalists/Hubble/index.html
Encyclopaedia Britannica, Inc. 1996, Hubble, Edwin Powell, http://www.gaiaguys.net/hubble.htm
Ryder, S. Dr., e-mail correspondence, Sept 7, 2005.
Europe Education Program, http://www.eso.org/outreach/eduoff/edu-prog/catchastar/CAS2002/cas-projects/bulgaria_magclouds_1/
Liverpool John Moores University, Astrophysics Research Institute, http://www.astro.livjm.ac.uk/courses/phys134/distance.html

ACKNOWLEDGEMENTS

This paper was prepared by the author as part of the curriculum requirement of ©Swinburne Astronomy Online (SAO). Thanks to Dr. Stuart Ryder (SAO) and Joanie Mickle for editorial comments.