Interferometry and the Cepheid Distance Scale

Thomas G. Barnes, III
82 Mt. Locke Road, McDonald Observatory, TX 79734; tgb@astro.as.utexas.edu

Presented at the 100th Spring Meeting of the AAVSO, May 23, 2011; received February 9, 2012; accepted February 10, 2012

Abstract Systematic uncertainties in the Cepheid distance scale have been greatly reduced in recent years through stellar interferometric observations. Interferometry has made possible direct measurement of Cepheid distances through interferometric pulsation distances. These results compare very well with recent Hubble Space Telescope trigonometric distances. Interferometry has also demonstrated that infrared surface brightness distances are quite reliable, making possible direct comparison of Cepheid luminosities in the Galaxy and the Magellanic Clouds.

1. Introduction

This year is the centennial of Henrietta Leavitt's discovery of the period-luminosity relation for classical Cepheid variables (Leavitt and Pickering 1912). In honor of Leavitt's discovery, the Cepheid period-luminosity relation is now usually called the Leavitt Law. This year is a good time to see just how far we have come in calibration of the Leavitt Law in the preceding century.

Leavitt's discovery made use of Cepheids in the Small Magellanic Cloud, all of which are sensibly at the same distance from us. A plot of their apparent magnitudes versus log (P) thus demonstrates the Leavitt Law (Figure1). Within the Galaxy, Cepheids are not so conveniently located. We must combine many individual distances to Cepheids to establish the relation. It has proved to be a very difficult task to achieve the accuracy that we desire in the relation. New techniques have significantly improved the situation.

Much of the progress is based on trigonometric parallax measures made with the Hubble Space Telescope (HST; Benedict *et al.* 2007) and on pulsation distances made with stellar interferometers. In the following I discuss the interferometric distances and then compare them with HST parallaxes. A more extensive review has been given by Barnes (2009).

2. Cepheid distance measurements

There are four principal means for determining Cepheid distances: open cluster distances, infrared surface brightness distances, interferometric pulsation distances, and trigonometric parallax distances.

2.1. Open cluster distances

There are twenty-four Cepheids known to be members of Galactic open clusters and associations (Turner 2010). Using the cluster main sequence fitting method, we may determine a distance to each cluster and thus to the Cepheids within them. This is accomplished in a color-magnitude diagram by comparing the apparent magnitudes of stars on the main sequence of the cluster to the absolute magnitudes of main sequence stars in a cluster at a known distance. The displacement in magnitude is attributed to distance. A good example of this method in application is given by Turner (1986) for S Nor in the cluster NGC 6087. Ever since Cepheids were discovered in open clusters (Irwin 1955), this has been the preferred method for establishing the Cepheid distance scale.

Cluster distances are limited in precision by several effects. Open clusters lie in the Galactic plane and are usually affected by considerable interstellar reddening. Correcting for the reddening is difficult, and the difficulty is often compounded by changes in the reddening across the face of the cluster. A second effect comes from the varying metal abundances of open clusters. The main sequence location in the color-magnitude diagram can change with metal abundance, impacting the distance measurement. Finally, the number of Cepheids in open clusters is modest, which affects our ability to define the Leavitt Law well. The table in Turner (2010) shows that Cepheid distances based on open cluster distances have precisions in the range ± 4–22%. Fouqué *et al.* (2007) have demonstrated that open cluster distances are fully consistent with distances from the infrared surface brightness technique and trigonometric parallaxes.

2.2. The Infrared Surface Brightness Technique

As a Cepheid variable pulsates, the photosphere expands and contracts relative to deeper layers of the star. The linear motion of the photosphere along the line of site to the Cepheid can be measured through the Doppler effect, that is, a radial velocity curve. An integration of the radial velocity curve, with appropriate correction for geometric and atmospheric effects, gives the linear distance that the surface moves over a pulsation cycle. The angular motion of the surface perpendicular to the line of site can be inferred from photometric measurements through a method called the surface brightness technique, introduced by Barnes and Evans (1976). The method was later improved by using infrared (VK) photometry (Welch 1994; Fouqué and Gieren 1997). The Infrared Surface Brightness Technique is an improvement upon the well-known Baade-Wesselink method for Cepheid radius determination.

By matching the angular distance traveled to the linear distance traveled, we can determine the distance through simple trigonometry. The beauty of the method is that it is applicable to any Cepheid for which radial velocities and infrared photometry may be measured. This puts Cepheids throughout the Local Group of galaxies within range of individual distance measurements.

The method was suspect early in its use for two reasons. First, the conversion of the photometric measurements into angular distances was thought to be subject to potential systematic errors. Second, the conversion of radial velocity into true pulsational motion could be subject to additional systematic errors. These concerns were finally put to rest. Kervella *et al.* (2004c) showed that angular diameters inferred from the infrared surface brightness technique were fully compatible with diameters found using interferometry. This resolved the photometric issue. Regarding the radial velocity correction, Barnes (2009) and Storm *et al.* (2011a) compared determinations of Cepheid distances using the infrared surface brightness technique, which depends on this correction, to trigonometric determinations, which do not, and found excellent agreement at the few percent level.

Storm *et al.* (2011a) applied the infrared surface brightness technique to 111 Cepheids in the Galaxy and the Magellanic Clouds. The mean precision in distance was better than ± 5%, with a range of 2–16%.

2.3. Interferometric pulsation distances

For relatively bright Cepheids, stellar interferometers can now measure the angular diameter of the Cepheid directly as it pulsates. Once again, the angular distance traveled by the photosphere (from interferometry) is matched to the linear distance traveled (from integrated radial velocities). This method eliminates the photometric inference involved in the infrared surface brightness technique.

A new, potential uncertainty is introduced. The conversion of interferometric observations into angular diameters for Cepheids requires prior knowledge of the Cepheid limb darkening, which is obtained from theoretical models; there may be errors in those models although the uncertainty is expected to be small in the infrared. Any errors in conversion of the radial velocities to linear distances remain in this method.

There are eight Cepheids for which distances have been determined this way (Table 1). The most distant is *l* Car at 525 parsecs. This distance method produces distances precise to ± 2–45%.

2.4. Trigonometric distances

Trigonometric parallaxes are the gold standard, geometric method for measuring distances. There are very few assumptions that enter into the method. However, Cepheids are distant and their parallaxes are small which has made determination of their distances by trigonometry very difficult. Recently the HST Fine Guidance Sensor was used to determine trigonometric distances to ten Cepheids (Benedict *et al.* 2007) as listed in Table 2. The most distant one is T Vul at 526 parsecs (coincidentally similar to the above distance to *l* Car). The precisions are ± 4–14%.

3. Stellar interferometry

Stars are frustratingly small in angular size on the sky. The largest stellar disk (other than the Sun) is less than 0.06 arcsecond across. The largest Cepheid angular diameter is that for *l* Car which is twenty times smaller. The change in angular size due to its pulsation is five times smaller yet. (For a list of angular diameters of bright Cepheids, see Moskalik and Gorynya 2006.) Cepheid diameters are far below the capabilities of even the largest single telescopes to measure. It takes a special technique to measure such small angles.

It is impossible in this short paper to do justice to the principles of interferometry. For a summary see Hajian and Armstrong (2001). The basic concept of stellar interferometry is most easily understood using the wave nature of light. Consider two separate telescopes viewing the same star as shown in Figure 2. After correcting for the different distances of the two telescopes from the star, the wavetrains arriving at the two telescopes are interfered to form a "fringe pattern." As the telescopes are moved further apart, the fringe pattern changes in a manner that depends on the stellar angular diameter and the separation of the telescopes. This change is quantified in a parameter called the "visibility" as shown in Figure 3. If the star is a point source the visibility does not change with baseline. On the other hand, the larger the stellar angular diameter, the sharper the visibility pattern and thus the easier it is to measure the diameter. Adding additional telescopes to the system can improve the capabilities of the interferometer.

There are four stellar interferometers that have measured the change in angular diameter as the Cepheid goes through its pulsation cycle. The following list gives the name, citation for a description of the interferometer, the baseline used for the Cepheid observations, and the Cepheids for which measured angular diameter variations were obtained. Not all of these interferometers are still in operation.

1) Palomar Testbed Interferometer; three 0.4 m telescopes with a 110-m baseline (Colavita *et al.* 1999): η Aql (in 2002), ζ Gem (2002);

2) Very Large Telescope Interferometer; two 8-m telescopes with two 0.35-m siderostats with a 140-m baseline (Glindemann *et al.* 2000; Kervella *et al.* 2003): η Aql (2004), W Sgr (2004), β Dor (2004), *l* Car (2004);

3) Center for High Angular Resolution Astronomy; six 1-m telescopes up to a 313-m baseline (ten Brummelaar *et al.* 2003): δ Cep (2005), Y Oph (2007), Y Sgr (2007); and

4) Sydney University Stellar Interferometer; 0.14-m telescopes with a 40-m baseline (Davis *et al.* 1999): β Dor (2006), *l* Car (2009).

4. Interferometric pulsation distances

A good example of a Cepheid distance by interferometry is that for *l* Car (Davis *et al.* 2009) obtained with the Sydney University Stellar Interferometer. In Figure 4 Davis *et al.* (2009) show the radial velocity curve assembled from several sources. This velocity variation is integrated and corrected for projection and atmospheric effects to obtain a curve showing the movement of the atmosphere over the pulsation cycle (not shown here).

Figure 5 shows the angular diameters measured using SUSI (symbols in the figure). The mean angular diameter is 2.99 ± 0.01 mas. The amplitude of the variation is 0.56 mas with a typical uncertainty on each datum of ±0.035 mas.

This measurement is equivalent to watching a 5.5-m ball on the surface of the moon vary in size by ±50 cm and measuring the variation with a precision of ±6 mm. It is a remarkable, technical achievement.

In Figure 6 Davis *et al.* show the measured angular diameters against the linear displacement at the same phase in the pulsation. The slope of the fit is inversely related to the distance and the zero point of the fit, to the mean angular diameter. They determined a distance of 525 ± 26 parsecs, the mean angular diameter quoted above, and a linear radius for the Cepheid of 169 ± 9 solar radii. The linear displacements are scaled to the distance and to the measured linear diameter to obtain the smooth curve in Figure 5. The curve fits the observed angular diameters well without any systematic deviations.

5. Discussion

Figure 7 demonstrates that interferometric pulsation distances determined for Cepheids are fully compatible with trigonometric distances. Unfortunately there are few additional Cepheids for which interferometry and trigonometry can provide new distances with current instruments. Thus the importance of the agreement between the two methods lies in the demonstration that a distance determined from the pulsation of a Cepheid is as accurate, and sometimes as precise, as a trigonometric distance.

Recall from the discussion of the infrared surface brightness method that it has been shown to give angular diameters in agreement with those from stellar interferometers. That result, combined with the excellent agreement between interferometric pulsation distances and trigonometric distances, gives us confidence that distances from the infrared surface brightness method are reliable. This has recently been demonstrated by Storm *et al.* (2011a, 2011b). They have determined distances to 111 Cepheids in the Galaxy, LMC and SMC using this method. The infrared K magnitude Leavitt Law they obtained is shown in Figure 8. The scatter about the relation is ±0.22 magnitude.

I believe Henrietta Leavitt would be pleased.

6. Acknowledgements

The author thanks Dr. Hal McAlister for permission to use two of his figures, and Dr. Antoine Mérand for permission to quote an unpublished result. The author also thanks Dr. G. Fritz Benedict for his review of the draft of this paper.

References

Barnes, T. G. 2009, in *Stellar Pulsation: Challenges for Theory and Observation*, eds. J. Guzik and P. Bradley, AIP Conf. Ser., 1170, Amer. Inst. Physics, Melville, New York, 3.

Barnes, T. G., and Evans, D. S. 1976, *Mon. Not. Roy Astron. Soc.*, **174**, 489.

Benedict, G. F., *et al.* 2007, *Astron. J.*, **133**, 1810.

Colavita, M. M., *et al.* 1999, *Astrophys. J.*, **510**, 505.

Davis, J., Ireland, M. J., Jacob, A. P., North, J. R., Owens, S. M., Robertson, J. G., Tango, W. J., and Tuthill, P. G. 2006, in *Advances in Stellar Interferometry*, eds. J. D. Monnier, M. Schöller, and W. C. Danchi, Proc. SPIE, 6268, SPIE, Bellingham, WA, 4.

Davis, J., Jacob, A. P., Robertson, J. G., Ireland, M. J., North, J. R., Tango, W. J., and Tuthill, P. G. 2009, *Mon. Not. Roy. Astron. Soc.*, **394**, 1620.

Davis, J., Tango, W. J., Booth, A. J., ten Brummelaar, T. A., Minard, R. A., and Owens, S. M. 1999, *Mon. Not. Roy Astron. Soc.*, **303**, 773.

Fouqué, P., and Gieren, W. G. 1997, *Astron. Astrophys.*, **320**, 799.

Fouqué, P., *et al.* 2007, *Astron. Astrophys.*, **476**, 73.

Glindemann, A., *et al.* 2000, in *Interferometry in Optical Astronomy*, eds. P. J. Lena, A. Quirrenbach, Proc. SPIE, 4006, SPIE, Bellingham, WA, 2.

Hajian, A. R., and Armstrong, J. T. 2001, *Scientific American*, **284**, 48.

Irwin, J. B. 1955, *Mon. Not. Astron. Soc. South Africa*, **14**, 38.

Kervella, P., Bersier, D. Mourard, D., Nardetto, N., Fouqué, P., and Coudé du Foresto, V. 2004c, *Astron. Astrophys.*, **428**, 587.

Kervella, P., Fouqué, P., Storm, J., Gieren, W. P., Bersier, D., Mourard, D., Nardetto, N., Coudé du Foresto, V. 2004a, *Astrophys. J., Lett. Ed.*, **604**, L113.

Kervella, P., Nardetto, N., Bersier, D., Mourard, D., and Coudé du Foresto, V. 2004b, *Astron. Astrophys.*, **416**, 941.

Kervella, P., *et al.* 2003, in *Interferometry for Optical Astronomy II*, ed. W. A. Traub, Proc. SPIE, 4838, SPIE, Bellingham, WA, 858.

Lane, B. F., Creech-Eakman, M. J., and Nordgren, T. E. 2002, *Astrophys. J.*, **573**, 330.

Leavitt, H. S., and Pickering, E. C. 1912, *Circ. Harvard Coll. Obs.*, **173**, 1.

McAlister, H. A. 2012, private communication.

Mérand, A. 2012, private communication.

Mérand, A., *et al.* 2005, *Astron. Astrophys.*, **438**, L9.

Mérand, A., *et al.* 2007, *Astrophys. J.*, **664**, 1093.

Moskalik, P., and Gorynya, N. A. 2006, *Mem. Soc. Astron. Ital.*, **77**, 253.

Storm, J., Gieren, W., Fouqué, P., Barnes, T. G., Soszyński, G., Pietrzyński, G., Nardetto, N., and Queloz, D. 2011b, *Astron. Astrophys.*, **534**, A95.

Storm, J., *et al.* 2011a, *Astron. Astrophys.*, **534**, A94.

ten Brummelaar, T. A., McAlister, H. A., Ridgway, S. T., Turner, N. H., Sturmann, L., Sturmann, J., Bagnuolo, W. G. Jr., and Shure, M. A. 2003, in *Interferometry for Optical Astronomy II*, ed. W. A. Traub, Proc. SPIE, 4838, SPIE, Bellingham, WA, 69.

Turner, D. G. 1986, *Astron. J.*, **92**, 111.

Turner, D. G. 2010, *Astrophys. Space Sci.*, **326**, 219.

Welch, D. L. 1994, *Astron. J.*, **108**, 1421.

Table 1. Cepheids with interferometric pulsation parallaxes. Adapted from Fouqué *et al.* 2007.

Star	*Log P (days)*	*π (mas)*	*σ(π) (mas)*	*Distance (pc)*	*σ(d) (%)*	*Source*
δ Cep	0.72	3.52	0.10	284	2.8	Mérand *et al.* (2005)
Y Sgr	0.76	1.96	0.62	587	30.6	Mérand *et al.* (2012)
η Aql	0.85	3.31	0.05	302	1.5	Lane *et al.* (2002)
W Sgr	0.88	2.76	1.23	362	44.6	Kervella *et al.* (2004b)
β Dor	0.99	3.05	0.98	328	3.1	Kervella *et al.* (2004b), Davis *et al.* (2006)
ζ Gem	1.01	2.91	0.31	344	10.6	Lane *et al.* (2002)
Y Oph	1.23	2.16	0.08	463	3.7	Mérand *et al.* (2007)
l Car	1.55	1.90	0.07	525	4.9	Kervella *et al.* (2004a), Davis *et al.* (2009)

Table 2. Cepheids with trigonometric parallaxes from Benedict *et al.* 2007.

Star	*Log P (days)*	*π (mas)*	*σ(π) (mas)*	*Distance (pc)*	*σ(d) (%)*
RT Aur	0.57	2.40	0.19	417	7.9
T Vul	0.65	1.90	0.23	526	12.1
FF Aql	0.65	2.81	0.18	356	6.4
δ Cep	0.73	3.66	0.15	273	4.0
Y Sgr	0.76	2.13	0.29	469	13.6
X Sgr	0.85	3.00	0.18	333	6.0
W Sgr	0.88	2.28	0.20	438	8.8
β Dor	0.99	3.14	0.16	318	5.1
ζ Gem	1.01	2.78	0.18	360	6.5
l Car	1.55	2.01	0.20	497	9.9

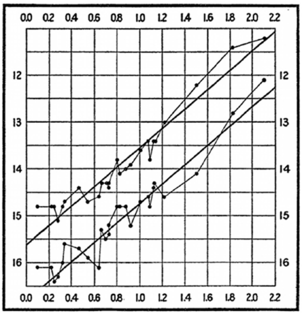

Figure 1. The first Cepheid period-luminosity relation as found in the Small Magellanic Cloud. Apparent magnitude at maximum light and at minimum light vs. log (period) for 25 variables. From Leavitt and Pickering (1912).

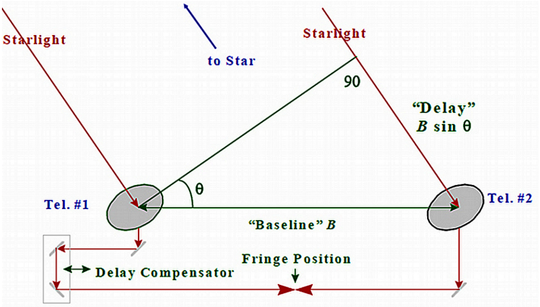

Figure 2. A simple interferometer. Figure courtesy of McAlister (2012).

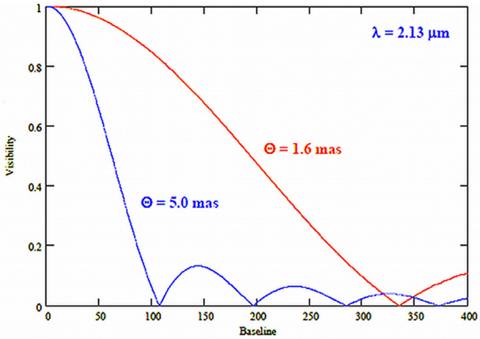

Figure 3. Examples of visibility curves for two different angular diameters. The separation of the telescopes (baseline) is given in meters. The units of angular diameter in the figure are milliarcseconds (mas). Courtesy of McAlister (2012).

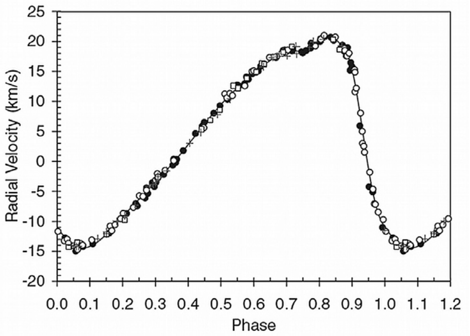

Figure 4. The radial velocity variation as a function of pulsation phase for the atmosphere of the Cepheid *l* Car. Courtesy of Davis *et al.* (2009).

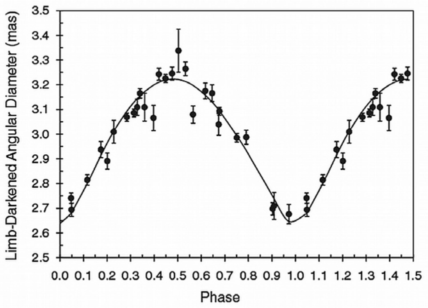

Figure 5. The observed angular diameter variation of *l* Car (symbols) and the linear displacement variation scaled to the measured distance (curve). Courtesy of Davis *et al.* (2009).

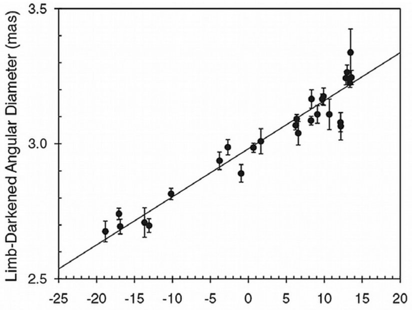

Figure 6. The fit of the angular diameter variation onto the linear variation for *l* Car. Courtesy of Davis *et al.* (2009).

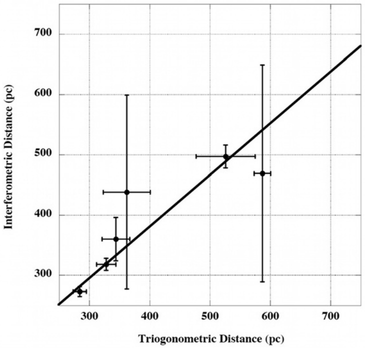

Figure 7. A comparison of interferometric pulsation distances to trigonometric distances for Cepheids. η Aql and Y Oph do not have trigonometric distances and are not plotted.

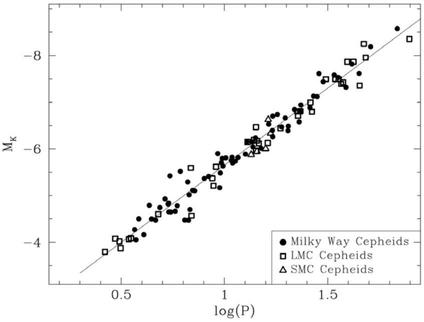

Figure 8. The Leavitt Law in the K magnitude based on Galactic, LMC, and SMC Cepheids. Courtesy of Storm *et al.* (2011a).