Distances to Classical Pulsators

Jesper Storm[1]

1. Leibniz-Institut für Astrophysik Potsdam
An der Sternwarte 16
14482 Potsdam, Germany

Cepheids and RR Lyrae stars are classical radial pulsators, and they remain fundamental standard candles. They are crucial for the determination of distances to distant galaxies and eventually the determination of the Hubble constant but also as important tracers of Galactic structure and evolution. *Gaia* will soon provide very precise zero points for the luminosities for these stars, and the present paper will highlight the status of the present calibrations and some of their shortcomings in view of the upcoming *Gaia* results.

1 Historical Background

Henrietta Leavitt (Leavitt & Pickering, 1912) discovered the correlation between stellar luminosity and the period of the light curve variation for Cepheids in the Small Magellanic Cloud (SMC). Shortly thereafter, Hertzsprung (1913) made the first calibration of the luminosity scale based on a statistical parallax argument for nearby Cepheids; thereby, determining the zero point of the period-luminosity relation. He found a distance of 3000 light years, and when he compared that with the scale height, which he had determined for the Milky Way, he concluded that the SMC was not part of the Milky Way. This could well be the first detection of an extragalactic object even if the concept of galaxies was not developed at the time. Hertzsprung immediately saw the potential for comparing the luminosities of different classes of stars in the SMC. This potential is still being exploited today, in particular, in the Large Magellanic Cloud (LMC), to compare and to calibrate the various standard candles employed in the quest for the extragalactic distance scale and the determination of the Hubble constant. Still, over a hundred years after Leavitt's discovery and Hertzsprung's calibration of the period-luminosity relation, Cepheids remain fundamental anchors for the distance scale (Freedman et al., 2001; Sandage et al., 2006). More recently the *SH0ES* project (Riess et al., 2009, 2011, 2016) also relies on Cepheids to derive distances directly to supernova host galaxies, thus calibrating the SNIa standard candles, which are then in turn used to measure the local value of the Hubble constant. RR Lyrae stars are also attracting new attention for extragalactic work with *Spitzer* (Scowcroft et al., 2011) and *Hubble Space Telescope* (*HST*) (Freedman, 2014).

2 Motivation

The Hubble Key Project on the determination of the Hubble constant (Freedman et al., 2001) reached a precision of about 10% in their determination of the Hubble constant. In the meantime, the study of the baryonic acoustic oscillations imprinted on the Cosmic Microwave Background in the early Universe has become feasible, using e.g. the *WMAP* (Hinshaw et al., 2013), and more recently, the *Planck* (Planck Collaboration et al., 2016) satellites. As shown by e.g. Beaton et al. (2016), these new high-precision results start to show differences with the most recent and most precise results from the Cepheid-based Hubble constant determinations (e.g. Riess et al. (2016)). The disagreement, if real, would have significant consequences for the standard cosmological model, and it is therefore very important to improve the precision even further.

3 Cepheids and RR Lyrae Stars as Distance Indicators

Cepheids and RR Lyrae stars are both radially pulsating variable stars found in the instability strip in the Hertzsprung-Russell diagram. They are excellent distance indicators as they follow a tight period-luminosity relations in the near-IR, and in the case of the Cepheids, also in the optical bands. The RR Lyrae stars furthermore follow a metallicity-luminosity relation. This is less relevant for extragalactic work where abundances are not readily available but very important for determining distances to Galactic globular clusters. Both types of stars are easily identifiable from their magnitude variation, which in the optical bands reaches an amplitude of more than 1 magnitude. The RR Lyrae stars have pulsation periods of less than a day whereas Cepheids have periods from about 2 to more than 100 days.

Cepheids and RR Lyrae stars belong to two very different stellar populations. The Cepheids are very bright ($-2 < M_V < -7\,\mathrm{mag}$), massive ($> 6\,\mathrm{M}_\odot$), and thus young ($< 400\,\mathrm{Myr}$) Pop-I stars typically found in or near star forming regions. RR Lyrae stars, on the other hand, are less bright ($M_V \approx +1\,\mathrm{mag}$), very evolved stars that belong to the oldest ($> 10\,\mathrm{Gyr}$) population in our own and other galaxies. This difference has important consequences for their application as standard candles. Cepheids are much brighter and can thus be observed to larger distances, but they tend to be found in dense star forming regions where accurate photometry can be difficult and where reddening can vary significant. RR Lyrae stars, on the other hand, are found in galactic halos where crowding and reddening issues are much less significant, and thus the systematic effects from these sources are much reduced. So in spite of being significantly fainter than Cepheids, this provides an attractive independent way to determine extragalactic distances.

4 The Cepheid Period-luminosity (PL) Relations

4.1 The slopes

Henrietta Leavitt discovered the PL-relation in the Small Magellanic Cloud as the stars are all at more or less the same distance to us. It turns out that the LMC is an even better place to compare luminosities, as it shows a much less complex 3D structure as the SMC, and the young population is basically a thin, slightly tilted disk seen almost from above (e.g. van der Marel & Cioni 2001 and references therein). A nice illustration of the Cepheid distribution in the Magellanic Clouds can be found in Soszyński et al. (2015) based on the OGLE survey (Udalski et al., 1999). The Large Magellanic Cloud is thus the preferred place to determine the slope of the

PL-relation. Soszyński et al. (2015) have determined the apparent PL-relation in the LMC in the V and I-bands as well as the Wesenheit index W_{VI} based on 4620 fundamental mode Cepheids:

$$\begin{aligned} V &= -2.690\log(P) + 17.438 \qquad \sigma = 0.208\,\mathrm{mag}\,, & (1)\\ I &= -2.911\log(P) + 16.822 \qquad \sigma = 0.146\,\mathrm{mag}\,, & (2)\\ W_{VI} &= -3.314\log(P) + 15.888 \qquad \sigma = 0.077\,\mathrm{mag}\,. & (3) \end{aligned}$$

In the near-IR K-band, Persson et al. (2004) determined an extremely tight relation of 92 fundamental mode Cepheids with a dispersion of only 0.11 mag, without attempting to correct for the slight tilt of the LMC disk. They found:

$$K = -3.261\log(P) + 16.036 \qquad \sigma = 0.112\,\mathrm{mag}\,. \tag{4}$$

Macri et al. (2015), using a sample of about 1000 stars in the central parts of the LMC, similarly found a scatter of only 0.09 mag in the K-band, again underscoring the intrinsic potential of the K-band for distance determination.

Recently, Scowcroft et al. (2011), using the *Spitzer* space telescope, have obtained light curves in the 3.5 and 4.6μm IR-bands, finding similarly small dispersions. The main advantage of these bands is the very low sensitivity to reddening. On the other hand they might start to have issues with CO-band absorption and possibly IR excess (see e.g. Gallenne et al. this volume).

4.2 The zero points

To determine distances using these excellent empirical PL-relations, it is necessary to determine the absolute zero points. The most fundamental way to do this is to directly measure the parallax to a sample of nearby Cepheids. Another route is to determine the luminosity directly using Baade-Wesselink techniques or Zero Age Main Sequence (ZAMS) fitting. Finally one can also measure the distance to the LMC and infer the PL zero point on this basis.

The latter approach has been very popular in the past as the extragalactic distances are generally derived relative to the LMC relations. This makes it obvious which zero point has been used, even if the distance to the LMC has been much disputed in the past. Freedman et al. (2001), in their concluding paper on the *HST* Key Project to measure the Hubble constant, adopted a value of $(m-M)_0 = 18.50 \pm 0.1$ mag, and this has become a canonical value in the meantime. de Grijs et al. (2014) have culled the literature for LMC distance estimates and found a value of 18.49 ± 0.09 mag based on 233 values published in the period from 1990 to 2013. They were looking for possible publication bias but found that the most likely reason that many results are in good agreement is that the fundamental data and/or analyses are not entirely independent. Pietrzyński et al. (2013) presented a very precise LMC distance of $18.493 \pm 0.008(\mathrm{stat}) \pm 0.047(\mathrm{sys})$ based on a number of well separated late-type eclipsing binaries, again in good agreement with the canonical value.

The fact that many studies seem to agree on the LMC distance at the level of a few percent is of course reassuring, but it is still crucial to calibrate the PL-relations in a purely geometrical way by of determining accurate parallaxes to local Cepheids. The *Hipparcos* satellite just barely reached the most nearby Cepheids, and the results are based on very noisy data. Feast & Catchpole (1997) thus found a zero point that would imply an LMC distance of 18.70 ± 0.1.

Later, Benedict et al. (2007) used the *HST* Fine Guidance Sensors to measure geometric parallaxes to ten nearby Cepheids. They applied a Lutz-Kelker-Hanson correction of, on average, -0.06 mag, and this calibration would imply an LMC distance based on the OGLE PL-relation in the Wesenheit index of 18.50 ± 0.04 mag. Using it for the Persson et al. (2004) K-band relation would mean a value of 18.45 ± 0.04 mag. One issue with this investigation is that nine of the ten Cepheids have periods shorter than 11 days and thus shorter than Cepheids typically studied in distant galaxies. On the other hand, the Cepheids with the adopted *HST* parallaxes appear to follow the LMC PL-relation very well, also when including the longest period star ℓ Car.

A classical independent approach to Cepheid luminosities is the ZAMS fitting method where Cepheids that are members of open clusters can have their luminosity determined by adopting the cluster distance as determined by zero age main sequence fitting. Turner (2010), and references therein, has applied this technique to some twenty clusters and find good agreement with the LMC relation and excellent agreement with the zero point determined by Benedict et al. (2007).

Clementini et al. (2017) have shown the potential that the data from the *Gaia* satellite will have to settle this issue. We should be aware though that as shown above, the different LMC PL-relations are not in perfect internal agreement, so even knowing the zero point to a high accuracy does not mean that we know the distances with similarly high accuracy as the uncertainty on the photometric zero points, reddening corrections, and metallicity effects become dominant in the error budget.

The methods described so far have relied on the assumption that the Cepheids in the LMC are identical to those in the distant galaxies to be studied, but it is a valid concern that metallicity might affect the luminosities to a significant degree. *Gaia* will surely help here as it will observe Cepheids with a significant range of metallicities in the Milky Way, but a method that can be applied to nearby as well as distant Cepheids is called for to resolve this issue. The Baade-Wesselink method is excellently suited for this task. It has been used to derive distances and luminosities to the SMC (Storm et al., 2004), LMC (Gieren et al., 2005; Storm et al., 2011b; Groenewegen, 2013), and Milky Way Cepheids, thus spanning a wide range of metallicities relevant for extragalactic distance determination. The method exploits the fact that radially pulsating stars allows the radius variation to be integrated over phase to give the absolute radius expansion and compare this to the angular diameter variation, which can be determined from other means (e.g. the surface brightness-color relation). The latter, in turn, is calibrated using interferometric measurements of nearby static stars as well as Cepheids (e.g. Kervella et al., 2004). For variations of the method, see Caccin et al. (1981); Molinaro et al. (2012, CORS, named after the authors), Mérand et al. (2015, SPIPS, SpectroPhoto-Interferometry of Pulsating Stars), and Storm et al. (2011a, IRSB, InfraRed surface-brightness).

4.3 Metallicity effects

In a classical paper, Kennicutt et al. (1998) observed Cepheids in a central and a peripheral field in the spiral galaxy M101 and found a small but significant luminosity difference of -0.24 ± 0.16 mag/dex where the metallicities were inferred from Oxygen abundances of HII regions. Much work has followed (see e.g. Romaniello et al. (2008) for an overview) using different methods, and the results have been showing a large range. Studies based on Magellanic Cloud Cepheids have the advantage of using stellar metallicities directly measured in Cepheids and young stars. We (Storm et al., 2011b) found a weak effect in the K-band of -0.12 ± 0.1 mag/dex and a stronger effect of -0.23 ± 0.1 mag/dex in the W_{VI} index using the Baade-Wesselink method to a sample of SMC, LMC, and Milky Way Cepheids. Recently, Wielgórski et al. (2017) found a null effect by comparing SMC and LMC Cepheids by adopting the eclipsing binary distance for each of the galaxies. This remains an open issue that is important to resolve to reduce the distance scale error to the 1% level.

5 RR Lyrae Stars

5.1 The [Fe/H] $- M_V$ *relation*

The RR Lyrae stars follow an $[\mathrm{Fe/H}] - M_V$ relation, but the slope has been difficult to constrain precisely. Four groups have studied the problem in detail using Baade-Wesselink methods, see Cacciari et al. (1992); Carney et al. (1992); Liu & Janes (1990); Fernley et al. (1990), and references therein. They found a shallow slope of about 0.2 in contrast to the work of Sandage (1990) based on period shifts. Gratton et al. (2004) found a similar shallow slope:

$$V_0 = 0.214([\mathrm{Fe/H}] + 1.5) + 19.064\,. \tag{5}$$

This is based on RR Lyrae stars in the LMC with individual spectroscopic metallicities.

Benedict et al. (2011) obtained geometric parallaxes for five RR Lyrae stars using the *HST* Fine Guidance Sensors. Adopting the relation for the LMC RR Lyrae stars from Gratton et al. (2004), they find a distance modulus in the V-band of 18.61 ± 0.05 mag. However using the V-band data from Soszynski et al. (2003) the modulus becomes 18.46 ± 0.06. Thus, there seems to be a significant photometric zero point issue here that would be very worthwhile to pursue.

5.2 The $\log P - M_K$ *relation*

Longmore et al. (1986) found that RR Lyrae stars appear to follow a PL-relation in the K-band. Longmore et al. (1990) suggested that there might be a slight metallicity effect as well. Dall'Ora et al. (2004) showed that the relation is extremely tight, finding a standard deviation of only 0.03 mag. The Baade-Wesselink work described above also included K-band data and could be used to calibrate the PL_K relation. Sollima et al. (2006) used RR Lyrae stars in globular clusters to delineate the PL-relation and found a small but insignificant metallicity effect. More recently, Muraveva et al. (2015) using K-band photometry from the VMC survey (Cioni et al., 2011), found the relation:

$$K_{s,0} = (-2.73 \pm 0.25)\log(P) + (0.03 \pm 0.07)[\mathrm{Fe/H}] + (17.43 \pm 0.01)\,. \tag{6}$$

Again, the metallicity effect seems to be insignificant.

Adopting the LMC distance from Pietrzyński et al. (2013) gives a zero point of −1.06, whereas adopting the Benedict et al. (2011) luminosities results in a zero point of −1.25, revealing a significant (0.2 mag) disagreement. The upcoming *Gaia* measurement of the zero point should enable us to resolve this outstanding problem.

For the RR Lyrae stars, *Spitzer* based PL-relations in the 3.6μm bands have also been presented by Marengo et al. (2017), who showed that when properly corrected for metallicity, the relation becomes exceedingly tight with a dispersion of only 0.02 mag.

6 What is Next

Gaia will determine zero points for the period-luminosity and luminosity-metallicity relations with unprecedented precision. It will also redetermine the zero points for the ZAMS fitting, affect the calibration of the Baade-Wesselink methods, and so on. This will make it necessary to redo the whole comparison process of the various methods, both within the Milky Way wherever possible but especially in the LMC. Chances are that we will find significant disagreements because we will be operating at a completely new level of precision. This will eventually lead to a much better physical understanding of the stars and have direct implications for cosmology. Still, we have to be very careful that systematic errors in the *Gaia* measurements are eliminated as early as possible as they will cascade down all branches of astrophysics and affect not only distance scales but also temperature scales and other fundamental relations. As shown here, we will also have to revisit the photometric calibrations of some of the basic distance indicators as it seems that systematics in photometric measurements, in some cases, still dominate over other uncertainties.

Acknowledgements. The financial support by the Polish Ministry of Science and Higher Education is gratefully acknowledged.

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