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How good are RR Lyrae and Cepheids really as distance indicators?

The observational approach

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Abstract. A number of recent technical developments, including the Hipparcos satellite, the Hubble Space Telescope fine guidance sensors and long base line near-IR interferometry has made it possible to employ several largely geometrical methods to determine direct distances to RR Lyrae stars and Cepheids. The distance scale now rests on a much firmer basis and the significant differences between the distances based on RR Lyrae stars (short) and Cepheids (long) to the LMC have been largely eliminated. The effects of metallicity on the RR Lyrae period-luminosity (PL) relation in the K-band as well as on the Cepheid PL relation appears to be the main remaining issues but even here empirical results are beginning to show convergence. I review here some of these recent developments seen from the perspective of the near-IR surface brightness method.

Key words. Cepheids – RR Lyrae stars – stars: distances – galaxies: distances and redshifts

1. Introduction

RR Lyrae stars and Cepheids are intermediate mass pulsating stars which are of fundamental importance for the calibration of the extragalactic distance scale. Recently significant progress has been made in obtaining largely geometric calibrations of these standard candles and a well founded consensus is finally starting to emerge regarding the distance to the Large Magellanic Cloud which provides the first step on the distance ladder as employed e.g. by the Hubble Space Telescope Key Project on the Extragalactic Distance Scale (Freedman et al. 2001).

2. The RR Lyrae stars

The RR Lyrae stars are valuable standard candles via the [Fe/H] $- M_V$ and $\log P - M_K -$ [Fe/H] (PLZ(K)) relations. The first relation is the most widely used as it is based on optical observational data. Unfortunately the relation exhibits a significant scatter and can only be considered an ensemble relation. Also the slope of the relation has been a contentious issue ranging from 0.16 to 0.30 (e.g. Jones et al. 1992, Sandage 1993) and the relation might not even be linear (see e.g. Caputo et al. 2000). The second relation, first discovered observationally by Longmore et al. (1986) and (1990), is potentially much more powerful as it exhibits a very low intrinsic scatter. D'Allora et al. (2004) observed an intrinsic scatter of only 0.026 mag for the (equal abundance) RR Lyrae stars in the LMC star cluster Reticulum. Recent theoretical work however, suggests that the metallicity effect is quite pronounced, of the order 0.2 mag/dex. Bono et al. (2003) finds:

$$M_K = -0.77 - 2.101 \log P + 0.231[\mathrm{Fe/H}] \quad (1)$$

while Catelan et al. (2004) finds:

$$M_K = -0.597 - 2.353 \log P + 0.175 \log Z \quad (2)$$

We have work in progress to observationally constrain this relation.

2.1. Trigonometric Parallax

The purest geometrical method which we have at our disposal for measuring distances to stars is to measure the trigonometric parallax. Hipparcos and HST have expanded very significantly the volume in space where this is feasible. Even so Hipparcos could barely reach one RR Lyrae star, namely RR Lyr itself, resulting in a fairly uncertain parallax measurement of 4.38 ± 0.59 mas, Perryman et al. (1997). More recently Benedict et al. (2002a) using the fine guidance sensor on HST found a value of 3.82 ± 0.20 mas, corresponding to $M_V = 0.61 \pm 0.1$ and $M_K = -0.56 \pm 0.1$ for an assumed absorption of $A_V = 0.07$. This is in excellent agreement with the value predicted by Eq.1 of −0.57. Due to the intrinsic width of the $[\mathrm{Fe/H}] - M_V$ relation this measurement can only constrain the zero point to within 0.13 mag (Cacciari and Clementini, 2003).

2.2. Statistical Parallax

The statistical parallax method assumes a dynamical model for the sample of stars being analyzed assuming that they belong to a dynamically well defined sample. Modern results from Layden et al. (1996) ($M_V = 0.71$ for $[\mathrm{Fe/H}] = -1.61$), Gould and Popowski (1998) ($M_V = 0.77$ for $[\mathrm{Fe/H}] = -1.6$) tend to support a faint magnitude of RR Lyrae stars when compared to other methods mentioned here. Applied to the LMC these results still support a short distance modulus. However, the method seems more and more isolated which suggests that the method might still suffer from systematic errors possibly related to the adopted models or due to unresolved biases in the observed samples.

2.3. Baade-Wesselink type analysis

The Baade-Wesselink type analysis gives accurate individual distances and absolute magnitudes to pulsating stars like RR Lyrae and Cepheids. Jones et al. (1992) derived a $M_V - [\mathrm{Fe/H}]$ for field RR Lyrae stars with a rather shallow slope. More recently Fernley et al. (1998) reanalyzed the available data and found

$$M_V = 0.20([\mathrm{Fe/H}] - 1.5) + 0.68 \quad (3)$$

For RR Lyr with a metallicity of $[\mathrm{Fe/H}] = -1.39$ this gives $M_V = 0.70$ and for the LMC adopting $[\mathrm{Fe/H}] = -1.5$ and $\langle V_0 \rangle = 19.07$ from Clementini et al. (2003) this leads to $(m - M)_0 = 18.39$. However, Cacciari et al. (2000) using revised model atmospheres etc for RR Cet found that the stars should be brighter by about 0.1 mag bringing these results very much into line with the canonical LMC distance (see Sec.3) as well as the trigonometric parallax result for RR Lyr itself.

More recently Kovacs (2003) applied the Baade-Wesselink method using new model atmospheres from Castelli et al. (1997). He found very good agreement with the implicit temperature scale from Fouqué and Gieren (1997) from the near-IR surface-brightness method. He also found good agreement between the RR Lyr and Cepheid distance scales to the LMC and found a best estimate of $(m - M)_0 = 18.55$, which is quite different from the short distance implied by the analysis by Jones et al. (1992).

2.4. ZAMS fitting to sub-dwarfs

The classical ZAMS fitting to globular clusters has recently been revisited by Gratton et al. (2003). They have used local sub-dwarfs with accurate Hipparcos parallaxes to determine distances to globular clusters by main sequence fitting in a very careful analysis. They find a relation

$$M_V = 0.22([\mathrm{Fe/H}] + 1.5) + 0.56 \quad (4)$$

Combining this with the observed $\langle V_0 \rangle = 19.07$ for the LMC RR Lyrae stars from Clementini et al. (2003) leads reassuringly to the canonical LMC distance of 18.51 ± 0.09.

3. The distance to the LMC

The distance to the LMC is used by the HST Key Project as the stepping stone to the extragalactic distances. They adopted a value of 18.50 ± 0.1. Recent reviews based on non-Cepheid distance estimates all tend to be in good agreement with this value. Walker (1999) found a value of 18.55 ± 0.1. Benedict et al. (2002a) averaged results from 80 recent studies using 21 different methods and found 18.47 ± 0.04, albeit with a large spread. Tammann, Sandage, and Reindl (2003) found 18.54 ± 0.02 based on 13 studies. Cacciari and Clementini (2003) found 18.48 ± 0.05 from 10 studies based only on RR Lyrae stars. Consequently it appears that the distance to the LMC is close to the value of 18.50 and methods which consistently gives results different from this value are likely to suffer from yet undetected systematic errors.

4. The Cepheids

4.1. The near-IR surface brightness method

The near-IR surface-brightness (ISB) method is a variant of the Barnes-Evans (Barnes and Evans, 1976) Baade-Wesselink type analysis. It has recently been calibrated by Fouqué and Gieren (1997) using interferometric measurements of non-pulsating giants and super giants. Gieren et al. (1998), applying this calibration to a sample of Galactic Cepheids, found that the zero point agreed well with that found for galactic open cluster Cepheids from ZAMS fitting. However, the slope of the derived galactic Cepheid PL relation was significantly steeper than observed in the LMC. If this effect is real it will have serious consequences for the application of the Cepheid PL relation as a distance indicator.

Most recently the method was applied to a sample of SMC Cepheids (Storm et al. 2004) and LMC Cepheids (Gieren et al. 2005, Storm et al. 2005). Storm et al. (2005), using a sample of Cepheids in the LMC star cluster NGC1866, determined the random error per star to be only 0.11 mag, somewhat larger than the estimated errors from the method. Barnes et al. (2005) have made a complete Bayesian statistical analysis propagating the errors through the method and they also find random errors of this order, suggesting that the method provides quite accurate distances to individual stars.

Gieren et al. (2005) showed that the ISB method applied to Galactic and LMC Cepheids, respectively, results in slopes which are indistinguishable, suggesting that the slope of the PL relation is at most very weakly dependent on the metallicity of the sample. However, the slopes remain different from the directly observed slopes in the LMC from OGLE2 (Udalski et al. 2000), as modified by Fouqué et al. (2003) and Persson et al. (2004). Gieren et al. (this volume) showed that the ISB distance estimates to the LMC Cepheids are period dependent, which of course is non-physical. The data is not yet entirely conclusive as the short period stars are all members of the cluster NGC1866. However, taken at face value they suggest that the conflict can be resolved by adopting a stronger period dependence of the project factor p which is used to convert the observed radial velocities into pulsational velocities. These pulsational velocities are used in the ISB method to determine the stellar distance and radius. The physical understanding of this effect is still lacking but one can consider the empirical adjustment of the p-factor as a way to parameterize the problem and thus reconcile all the observational data.

4.2. Interferometry

Very recently it has become possible to directly measure angular diameters of Cepheids. Nordgren et al (2002) reports results for 3 Cepheids using a number of interferometers, and Kervella et al. (2004a) reports results for 7 Cepheids using the VLTI. For the largest stars they even measure the angular diameter variation with phase. These results are truly impressive and provides fundamental geometrical constraints on the distance scale. Kervella et al. (2004b) have compared the results from interferometry with results from the ISB method for the largest (in an angular diameter sense) Cepheid in the sky, ℓ Car. The agreement is very good and with the rapidly expanding body of observational data we can already now employ the calibration of the surface-brightness relation from interferometry on Cepheids in the ISB technique. This means that we no longer have to rely on the assumption that the pulsating and non-pulsating stars follow the same relation, even though it turns out to be a fairly good assumption.

It is here important to remember that to derive distances and radii for the Cepheids the interferometric method also relies on the conversion of radial velocity data into pulsational velocities, just like the ISB method. Thus if the p-factor is period dependent as suggested by Gieren et al. (2005) then this would also have important consequences for the interferometrically determined distances and radii.

4.3. Trigonometric parallax

Hipparcos has measured trigonometric parallaxes for a large number of Cepheids (Feast and Catchpole (1997)). The individual errors are rather large but careful analysis results in a zero point which corresponds to an LMC distance of 18.7. Fouqué et al. (2003) revised the result to 18.50 by adopting the same LMC PL relation and reddening scale as employed by the HST key Project.

More recently Benedict et al. (2002b) have measured the trigonometric parallax to δ Cep using the HST fine guidance sensor. They found a value of $\pi_{\rm abs} = 3.66 \pm 0.15$ mas which corresponds to $M_V = -3.54$ for a visual extinction of $A_V = 0.30$ as adopted by Storm et al. (2004)). This compares reasonably well with the ISB result from Storm et al. (2004) of $M_V = -3.43$ but even better with the result after correcting the p-factor of $M_V = -3.59$ from Gieren et al. (2005).

4.4. ZAMS fitting and the Pleiades

Zero Age Main Sequence (ZAMS) fitting to open star clusters containing Cepheids using the Pleiades cluster or a theoretical ZAMS as a template was for a long time the most direct way to determine the zero point of the Cepheid PL relation. The Hipparcos satellite could tie this calibration in with a geometrical measure of the distance to the Pleiades. Unfortunately the Hipparcos measurements resulted in a very short distance, $(m - M) = 5.37 \pm 0.06$ (van Leeuwen (1999)) disagreeing substantially with previous measurements. This result provoked a surge of investigations to understand whether the Hipparcos result was wrong or that the understanding of the ZAMS fitting method itself was seriously flawed. A number of fundamental and largely geometrical distance determination methods have now been employed to objects in the Pleiades. Most recently Soderblom et al. (2005) have obtained parallaxes to three Pleiades stars using the HST fine guidance sensors finding a value of $(m - M) = 5.65 \pm 0.05$. These results agree well with recent ZAMS fitting results: 5.60 ± 0.04, Pinsonneault et al. (1998), 5.61 ± 0.03 Stello and Nissen (2001), 5.63 ± 0.05 Percival et al. (2005) as well as results from an eclipsing binary, 5.60 ± 0.05, Munari et al. (2004). Dynamical parallaxes for Atlas by Pan et al. (2004) and Zwahlen et al. (2004) further confirm this. Consequently there now seems to be a consensus that the ZAMS fitting scale as most recently propagated by Turner and Burker (2002) stand. van Leeuwen and Fantino (2005) have now re-reduced the complete Hipparcos dataset and the new results are eagerly awaited.

4.5. The effect of metallicity on the PL relation

It has long been suspected that the Cepheid PL relation might be affected by metallicity, but conclusive empirical evidence has remained elusive for a long time. Both on the slope and the zero-point of the relation can be affected.

Gieren et al. (1998) found a significantly different slope between the Galactic and LMC samples of Cepheids based on ISB analysis of Galactic Cepheids. This result has recently been revised by Gieren et al. (2005) after applying the ISB method directly to LMC Cepheids. This result is not conclusive yet, awaiting the analysis of a larger sample of LMC Cepheids. Tammann, Sandage and Reindl (2003) based partly on the Gieren et al. (1998) results also found a significantly different slope between the LMC and the Galactic Cepheids. On the other hand Udalski et al. (2001) did not find a significant difference between the low metallicity sample in IC1613 ([Fe/H] = −1.0) and the LMC ([Fe/H] = −0.5) suggesting that at least in this metallicity range there is not a significant effect.

The possible effect on the zero-point has also been elusive for a long time, but recent empirical data seems largely to agree on the sign and approximate size of the effect. As the effect is rather small it is also very difficult to measure. The best constraints can be obtained for PL relations with low intrinsic scatter and with a weak sensitivity to reddening, which of course are also the relations which are most useful for extragalactic distance determination. Currently these requirements are best met by the PL relation in the Wesenheits index as adopted by the Key Project and the *K*-band PL relation. It should be noted that the effect is likely to differ in different photometric bands.

The Key Project adopted a value of -0.20 ± 0.2 mag/dex for the metallicity sensitivity of the PL relation in the Wesenheits index in the sense that metal-rich Cepheids are brighter. This choice was largely based on the measurements presented by Kennicutt et al. (1998). These results have been confirmed more recently by e.g. Groenewegen et al. (2004) (-0.27 ± 0.08 mag/dex) from five MC Cepheids and 37 galactic Cepheids with individual metallicity measurements, by Storm et al. (2004) (-0.29 ± 0.19 mag/dex) from a differential analysis based on the ISB analysis of SMC and Galactic Cepheids[1]. Sakai et al. (2004) has performed an analysis of Cepheids in 17 galaxies with distances from the TRGB method and finds an effect of -0.24 ± 0.05.

Recent empirical investigations seems to agree, with a few exceptions, that the metallicity effect is fairly weak (-0.25 ± 0.1 mag/dex) and in the sense that metal rich Cepheids are brighter. The decisive measurement is still missing and the effect might well be non-linear and also depend on other chemical elements, in particular helium, as suggested by theoretical work of Fiorentino et al. (2002).

5. Conclusions

The distance to the Large Magellanic Cloud is converging on a value close to 18.50 ± 0.10 as adopted by the HST Key Project. Methods which give results significantly different from this value deserve closer scrutiny as there might be some important astrophysics to be learned.

The Cepheid PL relation remains the pivotal distance estimator and the effect of metallicity on the relation is the main remaining uncertainty. The issue of the supposedly different PL slopes between LMC and Galactic Cepheids might soon be fully resolved and the effect on the zero-point is similarly, at least from an empirical point of view, largely converging on a value not far from that adopted by the HST Key Project.

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[1] The conclusions regarding the metallicity effect in that paper are based on a purely differential measurement which is independent of any probable revisions of the *p*-factor, so this result stands even if the *p*-factor has a stronger dependence on luminosity.

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