# RR Lyrae Calibrations in the Light of *Gaia*

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In this presentation I review the impact of the *Gaia* DR1 TGas parallaxes on the RR Lyrae absolute magnitude calibrations on the period – $K_s$ and $W(B,V)$ relations I presented at the 2015 RR Lyrae Conference in Visegrad. A short and critical review of reddening determinations is given. *Gaia* gives me no reason to revise my calibrations. The dependence (slope) of the absolute visual magnitude $M_V$ on metallicity is rederived and found to be in agreement with the old proposal by Sandage (!).

## 1 Introduction

In my paper titled '$K - \log P$ is that all?', Lub (2016), I have argued that the apparent success of the IR ($K$, $W1$, [3.6] etc.) period-luminosity relation, ultimately, is due to the universal period-mass-radius relation, originally known as the $P\sqrt{\rho} = Q$ law. I also argue that this observational relation is UNIVERSAL.

A second relation for $W(B,V) = V - 3.06(B-V)$ falls into this category, because in this way the temperature dependence over the pulsation cycle of the variable star is minimized. To all appearances, its relation to $\log P$ is independent of metal abundance.

Calibration of these relations was done by combining the theoretical relations from the 'Framework' paper by Marconi et al. (2015), which I checked by using the astrometric parallaxes from *HST* by Benedict et al. (2011). There are only 5 stars, so I eagerly waited for the *Gaia* results.

## 2 *Hipparcos* Sample

In the previous paper, Lub (2016), I made use of a sample of about 40 stars with high quality visual and infrared photometry acquired by several groups in the past with a view towards Baade-Wesselink studies of RR Lyrae. Recently Monson et al. (2017) and Neeley et al. (2017) collected a similar sample and acquired additional photometry.

This time, however, the sample of about 146 RR Lyrae stars originally selected for the statistical parallax study with *Hipparcos*, see Fernley et al. (1998) and Feast et al. (2008), which has been well studied, was selected as my starting point.

In Visegrad (Lub, 2016), I discussed two period luminosity relations, viz:

$$K + 2.25 \log P = -1.06 + 0.18([\mathrm{Fe/H}] + 1.35),$$

$$W(B,V)_{\mathrm{theo}} = -1.06 - 2.49 \log P.$$

The equality of the two zeropoints is only fortuitous: as for the average RRab $\langle V - K \rangle = 1.05$ and similarly $\langle B - V \rangle = 0.35$. These compensate each other.

As a first step I compared the distance moduli or photometric parallaxes derived from both calibrations: not all stars have all required photometry available, but for the 114 stars in common, I find a very tight relation between $(m - M)_{K,0}$ vs. $(m - M)_W$ with a correlation coefficient 0.99733, slope 0.99052, and an average difference of $-0.036$ with a standard deviation of 0.078. This average difference could be reduced to zero by selecting a new zeropoint of $-1.09$ for $K - \log P$.

If I assume that these errors can be equally divided between $K$ and $W(B, V)$, this would mean that the photometric parallaxes have a relative error of 0.028 or 2.8% for a single measurement, whereas the systematic error can be no larger than 1.8%. These errors have the rewarding property of being independent of the star's brightness or parallax.

It may well be that the photometric errors on $K$ are smaller than those on $W(B, V)$, which is a combination of a magnitude and a colour whose errors, albeit of order slightly less than 0.01 are multiplied by a factor of three (!). All-sky IR photometry from many sources cannot be better than 0.025, the $V$ magnitudes are a mixture of *Hipparcos*, Walraven $VBLUW$, and various $UBV$ surveys and show no better external agreement than 0.015. To be added in is also the uncertainty due to the Blazhko effect, mostly for the visual photometry. On the other hand, the uncertainty of 0.15 dex in [Fe/H] adds another 0.03 random error to the results using $K$. I have chosen to use the $K$ photometry as my reference because of a more complete (larger) sample.

## 3 Additional Remarks on Reddening

Whereas the use of IR magnitude relations reduces the impact of interstellar absorption, because $A_K = 0.35E(B - V)$, it comes back with a vengeance as soon as these relations are used to calibrate absolute magnitudes in other wavelength ranges, because $A_K = 0.12A_V$.

A good start is the reddening (derived from dust emission) maps from the Wilkinson Microwave Anisotropy Probe (*WMAP*) by Schlegel et al. (1998) and Schlafly & Finkbeiner (2011). For high galactic latitudes, the RR Lyrae stars are mostly beyond the absorbing layer, whereas for intermediate and low galactic latitudes, I found that a correction can be estimated from the 'Parenago Factor' $X = 1 - \exp(-d \sin |b|/100)$, where $d$ is an educated 'first' guess of the star's distance. At any rate, this correction provides a warning that the *WMAP* estimate of $E(B - V)$ is overestimated as soon as it is significantly less than 0.99.

A further check can always be done – **and must be done** – from the available measurements of the $(B - V)$ colour: either from the minimum colours for RRab stars as done originally by Sturch (1966), or admittedly rather roughly from their mean colours for RRd and RRc stars: respectively, 0.26 and 0.21 (range for the latter: $0.18 - 0.24$).

I also reinvestigated the relation between the *WMAP* reddenings (including the factor $X$) and my study of RR Lyrae reddenings based on multicolour Walraven $VBLUW$ photometry (Lub, 1979). Improvement of my knowledge of the photometric system now shows that for RR Lyrae stars, $E(B - V)_J = 2.5E(V - B)_{VBLUW}$ is a better representation of the relation between the Johnson and Walraven measurements. There is perfect agreement within the errors of the photometry, with an average offset $\langle E(B-V)_{WMAP} - E(B-V)_{VBLUW}\rangle$ close to zero.

Feast et al. (2008) in their paper on RR Lyrae parallaxes from *Hipparcos*, mention that they use a reddening model, but their values are on the whole consistent with the *WMAP* values, in highly reddened cases with a correction based upon the observed colours, as used by me.

Recently, some worrying and (extremely) discordant determinations of $E(B-V)$ have seen the light: Klein & Bloom (2014) (unpublished; arXiv only) and Neeley et al. (2017). The former starts from the *WMAP* $E(B-V)$ and then derives values that are on average larger by 0.033, implying $A_V = 0.10$; the other derives for RRab values of $A_V$ that are 0.22 larger (!), whereas for RRc stars the difference is only 0.05, while at the same time the distribution over the sky of these two classes is not very different. Fortunately these values appear not to have been used any further in the mentioned paper.

Such values cause the intrinsic colours of RR Lyrae stars, which have been extensively studied in various surroundings and in relation to many other classes of stars in e.g. globular clusters, to shift out of the RR Lyrae instability strip. In addition, they make the visual absolute magnitudes much brighter than can be accommodated. They must therefore be considered to be of very doubtful value and need more investigation.

## 4 *Gaia*

As soon as the first data release from *Gaia* became available, I extracted the TGas data for the *Hipparcos* sample one by one in order to be able to get directly a feeling for the contents of the catalogue.

The *Hipparcos* sample has a limiting magnitude of order 11.5, equivalent to a parallax of about 0.5 mas. The median precision of the *Gaia* parallaxes is 0.230 mas, but there may still be locally systematic errors of the same order, see Gaia Collaboration et al. (2016). Out of 142 stars in my sample, I found:

1. Ten stars missing from the database, unfortunately well studied and bright stars with parallaxes on average larger than 1.0 mas.

2. Seven stars with large (unexplained) errors larger than 0.5 mas.

3. Six stars with extremely small parallaxes but typical errors (one negative parallax). Are they examples of those systematic errors? But there ought to be also similar cases in a positive sense.

As mentioned before, I shall be comparing photometric parallaxes with a 2.8% relative error independent of parallax, with astrometric parallaxes with a fixed error of order 0.230 mas independent of parallax. I have done so by comparing the differences: $\pi_{Gaia} - \pi_{phot}$ with $\pi_{phot}$ and forming averages. I have left the second and third category of stars mentioned above in this comparison in order to avoid unduly biasing the outcome. Inspection of the plot of these quantities against each other clearly shows a symmetrical distribution around zero.

In summary (all parallaxes are in mas):

- $K$: $N = 132$, average values $\langle[\mathrm{Fe/H}]\rangle = -1.38$, $\pi_K = 0.941$, $\pi_{Gaia} = 0.938$, $\pi_{Gaia} - \pi_K = 0.002 \pm 0.229$

- $W(B,V)$: $N = 105$, average values $\langle[\text{Fe/H}]\rangle = -1.30$, $\pi_{W(B,V)} = 0.995$, $\pi_{Gaia} = 1.000$, $\pi_{Gaia} - \pi_{W(B,V)} = 0.005 \pm 0.240$

This leaves hardly any room for a revision of the zeropoints adapted in my Visegrad paper (Lub, 2016). As will become clear below, I have refrained from further use of the *Gaia* parallaxes as I planned originally, in order to investigate the [Fe/H] dependence in my calibrations.

## 5 Absolute Magnitude $M_V$ vs. [Fe/H] Relation

Armed with my validation of the period – $K$ and $W(B,V)$ relations, I can now determine the absolute visual magnitudes as:

$$M_V = V_{obs} - A_V - 5\log(\pi) + 10,$$

where either $\pi_K$ or $\pi_{W(B,V)}$ in mas can be substituted.

As remarked previously in Lub (2016): the tight relation between Period and $K$ or $W(B,V)$ magnitude has direct consequences for the often used $M_V$ – [Fe/H] relation, which conventionally has a slope close to 0.21 e.g. Gratton et al. (2004). In contrast, Sandage (1993) has championed a value like 0.33. This relation has been often used as a constraint on deriving further properties of RR Lyrae stars, with the zeropoint set by the mean from the Baade-Wesselink method.

Above I have shown the equivalence of my 2 calibrations, and as my sample for $K$ is more extensive, I will only discuss my results using $\pi_K$. The results using $W(B,V)$ are no different. Inspection shows that it serves no purpose to make use of the *Gaia* parallaxes in order to calculate absolute magnitudes: they are still not precise enough to show up any definite relation between $M_V$ and [Fe/H].

A formal regression for my sample of 132 stars of $M_V$ on [Fe/H] gives a correlation of 0.8651, a slope of 0.332, and a mean $\langle M_V\rangle = 0.605 \pm 0.100$ at $\langle[\text{Fe/H}]\rangle = -1.30$. This leads to the relation in which the formal error on the zeropoint would be 0.009:

$$M_V = 0.590 + 0.335([\text{Fe/H}] + 1.35).$$

There appears to be no way out to this conclusion, except accepting a smaller abundance dependence in the $K - \log P$ relation by 0.10, but this then introduces a negative abundance dependence in the $W(B,V) - \log P$ relation of the same order.

## 6 Conclusions and Application to the LMC Distance

Just in time for the conference, I received the tables accompanying the paper by the *Gaia* team, Gaia Collaboration et al. (2017), with a sample of 202 RR Lyrae stars with $K$ magnitudes and *Gaia* parallaxes. The conclusions from those data, after correcting a few inaccuracies, are no different than those exposed above. After removal of BB Vir and V0363 Cas (the usual suspects one would say...) I have:

- $K$: $N = 200$, average values $\langle[\text{Fe/H}]\rangle = -1.38$, $\pi_K = 0.820$, $\pi_{Gaia} = 0.828$, $\pi_{Gaia} - \pi_K = 0.007 \pm 0.319$

Again, a regression of $M_V$ on [Fe/H] gives a correlation of 0.9316 and a slope of 0.336 and a mean $\langle M_V\rangle = 0.567 \pm 0.074$ at $\langle[\text{Fe/H}]\rangle = -1.38$ for $N = 198$ RR Lyrae. This would change the zeropoint of the relation to $0.577 \pm 0.005$ apart from any systematic error. This is clearly an improvement albeit small upon my result in the previous Section.

Making use of the RR Lyrae data in 2 LMC fields observed and extensively studied by Di Fabrizio et al. (2005), from which I have selected the best photometric measurements, which leaves 99 stars (RRab, RRd and RRc), I find that the average $\langle W(B,V) + 2.49 \log P \rangle = 17.455 \pm 0.100$ for a single measurement. A formal regression gives a slope of 2.52 for the period dependence, in agreement with my results. This leads to a distance modulus of $18.515 \pm 0.010$, in agreement with the overwhelming majority of determinations. On the other hand, my reanalysis of the $K$ measurements for the 70 stars belonging to the Muraveva et al. (2015) sample gives both a larger period dependence and distance modulus, which is in agreement with her results. This needs further thought.

It appears then that RR Lyrae stars (if their periods can be established) are indeed a powerful tool to study the Galaxy and the Local Group.

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