RR Lyrae stars as standard candles in the Gaia Data Release 2 Era

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ABSTRACT
We present results from the analysis of 401 RR Lyrae stars (RRLs) belonging to the field of the Milky Way (MW), for which multiband (V, Ks, W1) photometry, metal abundances, extinction values and pulsation periods are available in the literature and accurate trigonometric parallaxes measured by the Gaia mission have become available with the Gaia second data release (DR2) on 2018 April 25. Using a Bayesian fitting approach we derive new near- and mid-infrared period-absolute magnitude-metallicity (PMZ) relations and new absolute visual magnitude-metallicity (MV−[Fe/H]) relations based on the Gaia DR2 parallaxes of these 401 RRLs. We find the dependence of luminosity on metallicity to be higher than usually found in the literature, irrespective of the passband considered. Running the adopted Bayesian model on a simulated dataset we show that the high metallicity dependence is not caused by the method, but likely arises from the actual distribution of the data and the presence of a zero-point offset in the Gaia parallaxes. We infer a zero-point offset of −0.056 mas, with the Gaia DR2 parallaxes being systematically smaller. This value is in excellent agreement with the offset found by the Gaia validation team using a different sample of RRLs. In order to gauge our newly derived relations we use them to infer the distance to the Large Magellanic Cloud, which turns out to be in a good agreement with values currently adopted in the literature.

Key words: Parallaxes – stars: variables: RR Lyrae – galaxies: Magellanic Clouds – galaxies: distance

1 INTRODUCTION

Over the years, many different methods have been devised in order to measure distances in astronomy. However, techniques based on geometrical principles, among which the trigonometric parallax in first place, remain the most direct, simple and reliable tool to anchor the whole astronomical distance ladder on a solid basis. In the distance ladder approach, the limited horizon allowed by parallaxes is circumvented by making use of standard candles, such as, the RR Lyrae (RRL) variable stars, whose absolute calibration rests on parallax measurements of local samples of the class.

RR Lyrae stars (RRLs) are old (age > 10 Gyr), low mass (m< 1 M⊙), radially pulsating stars which populate the classical instability strip region of the horizontal branch (HB) in the colour-magnitude diagram (CMD). RRLs divide into fundamental (RRab) and first-overtone (RRc) mode pulsators and double-mode (RRd) variables, which pulsate in both modes simultaneously. RRLs serve as standard candles to measure distances since they conform to relations between the absolute visual magnitude and the metallicity (MV−[Fe/H]), and near- and mid-infrared period-absolute magnitude (PM) and PM-metallicity (PMZ) relations. The near-infrared PMKZ relation has a number of advantages in comparison with the visual MV−[Fe/H] relation, such as a smaller dependence of the luminosity on interstellar extinction (A_K=0.114A_V, Cardelli et al. 1989), metallicity and evolutionary effects. The effect of extinction is even less pronounced in the mid-infrared passbands. For instance, the extinction in the Wide-field Infrared Survey Explorer (WISE) W1 (3.4 μm) passband is roughly 15 times smaller than in the V band (A_W1= 0.065A_V, Madore et al. 2013). Furthermore, near- and mid-infrared light curves of RRLs have smaller amplitudes, hence, determination of the mean
magnitudes is easier and more precise than in visual bands further beating down the dispersion of their fundamental relations. Accurate trigonometric parallaxes for a significantly large sample of RRLs are needed to firmly calibrate their visual $M_V − [\text{Fe/H}]$ and near- and mid-infrared $PM_{W1}Z$ relations. This is what Gaia, a European Space Agency (ESA) cornerstone mission launched on 2013 December 19, is deemed to provide within a few years time-frame.

Gaia is measuring trigonometric parallaxes, positions, proper motions, photometry and main physical parameters for over a billion stars in the Milky Way (MW) and beyond (Gaia Collaboration et al. 2016a; Gaia Collaboration et al. 2016b). The Gaia first data release (DR1), on 2016 September 14, published positions, parallaxes and proper motions for about 2 million stars in common between Gaia and the Hipparcos and Tycho-2 catalogues, computed as part of the Tycho-Gaia Astrometric Solution (TGAS, Lindegren et al. 2016). The DR1 catalogue comprises parallaxes for 364 MW RRLs, of which a fraction were used by Gaia Collaboration et al. (2017) to calibrate the $M_V − [\text{Fe/H}], PM_KZ$ and $PM_{W1}Z$ relations. On 2018 April 25, the Gaia second data release (DR2), has published positions and multi-band photometry for ~1.7 billion sources as well as parallaxes and proper motions calculated solely on Gaia astrometry for ~1.3 billion sources (Gaia Collaboration et al. 2018). Furthermore, Gaia DR2 released a catalogue of more than ~500,000 variable stars of different types (Holl et al. 2018), that comprises 140,784 RRLs (Clementini et al. 2018) for which main characteristic parameters (period, pulsation mode, mean magnitudes, amplitudes in the Gaia $G$, $G_{BP}$ and $G_{RP}$ passbands, extinction and individual metal abundance ([Fe/H]) were also released. This provides an enormous contribution to the common knowledge of the variable star population in and beyond the MW.

A number of independent studies discussing a possible zero-point offset affecting the Gaia DR2 parallaxes appeared recently in the literature (e.g. Arenou et al. 2018; Riess et al. 2018; Zinn et al. 2018; Stassun & Torres 2018). All these studies agree on the Gaia DR2 parallaxes being systematically smaller (hence, providing systematically larger distances) than inferred by other independent techniques.

In this paper we use the accurate parallaxes available with Gaia DR2 for a large sample of local RRLs along with a Bayesian fitting approach to derive new $M_V − [\text{Fe/H}], PM_KZ$ and $PM_{W1}Z$ relations. The new relations are then used to measure the distance to RRLs in the Large Magellanic Cloud (LMC), where the accuracy of the trigonometric parallax measurements is hampered by the faint magnitude/large distance of the LMC RRLs. In doing so we also test the quality of Gaia DR2 parallaxes and the zero-point parallax offset.

The paper is organised as follows. In Section 2 we describe the sample of RRLs that we have used in this study. In Section 3 we perform a comparison of the DR2 parallaxes with the TGAS, Hipparcos and Hubble Space Telescope (HST) parallaxes and with photometric parallaxes inferred from Baade-Wesselink (BW) studies. The Bayesian fitting approach applied in our study is described in Section 4. The RRL $M_V − [\text{Fe/H}], PM_KZ$ and $PM_{W1}Z$ relations derived in this work and a discussion of the Gaia DR2 parallax zero-point offset are presented in Section 5. In Section 6 we use our newly derived relations to measure the distance to the LMC. Finally, a summary of the paper results and main conclusions are presented in Section 7.

2 DATA

2.1 Sample of RR Lyrae stars

In order to calibrate the $M_V − [\text{Fe/H}], PM_KZ$ and $PM_{W1}Z$ relations of RRL variables, one needs a large sample of RRLs with accurate photometry, the precise knowledge of their period and pulsation mode, metallicities spanning a large enough range, alongside an accurate estimation of the star parallaxes/distances. Following Gaia Collaboration et al. (2017) we select a sample of 403 MW field RRLs studied by Dambis et al. (2013), who have collected and homogenised literature values of period, pulsation mode, extinction in the visual passband ($A_V$), metal abundance ([Fe/H]) and intensity-averaged magnitudes in the Johnson $V$, 2MASS $K_s$ and WISE $W1$ passbands. Dambis et al. (2013) took the pulsation periods from the ASAS3 catalogue (Pojmanski 2002, Maintz 2005) and the General Catalogue of Variable Stars (GCVS, Samus et al. 2007-2015). The intensity-averaged $V$ magnitudes were calculated from nine overlapping sets of observations (see Dambis et al. 2013 and references therein for details); the $K_s$-band intensity-averaged magnitudes were estimated applying a phase-correction procedure described in Feast et al. (2008) to the 2MASS single epoch $K_s$ measurements of Cutri et al. (2003). Dambis et al. (2013) did not apply phase-corrections to 32 RRLs in their sample. For these objects we adopted the single-epoch $K_s$ magnitudes, however, thanks to the small amplitude of the RRL light curves in the $K_s$ band (typical $K_s$ amplitudes on the order of ~0.1 mag), this assumption does not affect significantly our results. The intensity-averaged $W1$ magnitudes were estimated by Dambis et al. (2013) from the WISE single-exposure data. Extinction values were inferred from the three-dimensional model of Drimmel et al. (2003). Individual uncertainties of the extinction values are not provided by Dambis et al. (2013), but Drimmel et al. (2003) compared their extinction estimates with those derived from the near-infrared CMD of MW fields based on 2MASS data and found differences smaller than 0.05 mag, which we adopt as the extinction uncertainty for all RRLs in our sample. The $V$, $K_s$ and $W1$ apparent magnitudes were corrected for interstellar extinction adopting $R_V = 3.1$, $A_K/A_V = 0.114$ (Cardelli et al. 1989, Caputo, Marconi & Musella 2000a) and $A_{W1}/A_V = 0.065$ (Madore et al. 2013). Dambis et al. (2013) calculated homogeneous metallicities on the Zinn & West (1984) metallicity scale, combining spectroscopically and photometrically measured metal abundances. Uncertainties of individual metallicities are not provided in the Dambis et al. (2013) catalogue. We assumed them to be of 0.1 dex for the stars that have metallicity estimates from high-resolution spectroscopy. An uncertainty of 0.2 dex was instead adopted for RRLs whose metal abundance was measured with the $\Delta S$ technique (Preston 1959) or for which we have not found the source of the metallicity estimate. Finally, we assigned a metallicity uncertainty of 0.3 dex to all stars, whose metallicity was obtained from photometry or other non-spectroscopic methods.

While working on this paper we became aware of
updated parameter values for some RRLs in our sample (J. Lub, private communication). Following these updates, we adopted a different period value than in Dambis et al. (2013) for six RRLs (namely, DH Peg, ER Aps, DN Aqr, DM Cyg, DD Hya, DH Hya) and the pulsation mode of DH Peg was changed to RRc, accordingly. The extinction values of CG Lib and RZ Cep were also revised. Finally, BB Vir turned out to be a blend of two stars and was hence discarded. On the other hand, the rather long period of BI Tel (P=1.17 days), would place the star in the Anomalous Cepheid domain. Hence, we decided to discard this RRL as well. Our final sample consists of 401 RRLs, of which 366 pulsate in the fundamental mode and 35 in the first overtone mode.

We have crossmatched our catalogue of 401 RRLs against the Gaia DR2 catalogue available through the Gaia Archive website\(^1\) using a cross-match radius of 4”, and recovered the DR2 parallaxes for all of them. The complete dataset, namely, identifications, parallaxes and positions from the Gaia DR2 catalogue, alongside the period, pulsation mode, extinction, metal abundance and mean V, K \(_s\) and W1 magnitudes available in the literature for these 401 RRLs, are provided in Table 1. The parallaxes of our sample span the range from \(-2.61\) mas to 2.68 mas, with seven RRLs having a negative parallax value, among which, unfortunately, is RR Lyr itself, the bright RRL that gives its name to the whole class (see Section 3.1). Uncertainties of the Gaia DR2 parallaxes for the 401 RRLs in our sample are shown by the red histogram in Fig. 1. They range from 0.01 to 0.61 mas. The position on sky of the 401 RRLs is shown in Fig. 2. They appear to be homogeneously distributed all over the sky, which makes any possible systematic spatially-correlated biases negligible. The apparent V mean magnitude of the 401 RRLs range from 7.75 to 16.81 mag. Adopting for the RRL mean V absolute magnitude \(M_V\)=0.59 mag at [Fe/H]=–1.5 dex (Cacciari & Clementini 2003) we find for our sample distance moduli spanning the range from \(\sim 7\) to \(\sim 16\) mag or distances from \(\sim 250\) to \(\sim 16,000\) pc. Periods and metallicities of the 401 RRLs also span quite large ranges, namely, from 0.25 to 0.96 days in period and from \(-2.84\) to \(+0.07\) dex in [Fe/H], with the metallicity distribution of the sample peaking at [Fe/H]=–1.5 dex. The distributions in apparent V mean magnitude, period and metallicity of our sample of 401 RRLs are shown in the upper, middle and lower panels of Fig. 3, respectively.

Regarding a possible selection bias, our sample is mainly affected by the selection process carried out in Dambis et al. (2013). The requirements set there have effects potentially stronger than most of the Gaia selection function characteristics (described qualitatively in Gaia Collaboration et al.

\(^1\) http://archives.esac.esa.int/gaia

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**Figure 1.** Distribution of the DR2 parallax uncertainties for our sample of 401 RRLs (red histogram) and the TGAS parallax uncertainties for the subsample of 199 RRLs for which TGAS parallaxes were published in Gaia DR1 (blue histogram). The bin size is 0.025 mas.

**Figure 2.** Sky distribution of our sample of 401 RRLs in Galactic coordinates. Red and blue filled circles show RRab and RRc stars respectively.

**Figure 3.** Distribution in apparent V mean magnitude (upper panel), period (middle panel) and metallicity (on the Zinn & West 1984 metallicity scale; lower panel) for the RRLs in our sample. V mean magnitudes are available for 382 RRLs in our sample of 401 variables, metallicities for 400 RRLs, while pulsation periods are available for the whole sample of 401 stars.
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Table 1. Dataset for the 401 RRLs: (1) name; (2) Gaia identifier; (3) and (4) coordinates in the Gaia DR2 catalogue; (5) Gaia DR2 parallax; (6) RRL type; (7) period; (8), (9) and (10) mean $V$, $K_s$ and $W_1$ magnitudes from Dambis et al. (2013); (11) metallicity on the Zinn & West (1984) metallicity scale; (12) extinction in the $V$ band.

| Name           | ID$_{Gaia}$ | RA  (deg) | Dec  (deg) | $\pi_{DR2}$ (mas) | Type  | $P$ (day) | $V$ (mag) | $K_s$ (mag) | $W_1$ (mag) | [Fe/H]  | $A_V$ |
|----------------|-------------|-----------|------------|-------------------|-------|----------|----------|------------|------------|--------|------|
| DR Ppeg        | 27260364552874775844 | 326.8569 | -0.2106 | 0.05 ± 0.05 | RRLs* | 7.9553 ± 0.077 | 8.603 ± 0.036 | 8.273 ± 0.078 | -1.36 ± 0.20 | 0.263  |
| DI Ape         | 5802753584019644664 | 282.3522 | -0.26 ± 0.02 | RRLs | 7.9553 ± 0.077 | 8.603 ± 0.036 | 8.273 ± 0.078 | -1.36 ± 0.20 | 0.263  |
| UV Cen         | 1134921385808398892 | 255.7452 | 0.26 ± 0.02 | RRLs | 7.9553 ± 0.077 | 8.603 ± 0.036 | 8.273 ± 0.078 | -1.36 ± 0.20 | 0.263  |
| TV Lib         | 6218131342429050480 | 229.5912 | -0.26 ± 0.02 | RRLs | 7.9553 ± 0.077 | 8.603 ± 0.036 | 8.273 ± 0.078 | -1.36 ± 0.20 | 0.263  |
| YZ Cap         | 484361748298029488 | 510.8650 | -0.26 ± 0.02 | RRLs | 7.9553 ± 0.077 | 8.603 ± 0.036 | 8.273 ± 0.078 | -1.36 ± 0.20 | 0.263  |

* Parameters were changed according to updated informations. See text for the details.

This table is published in its entirety at the CDS; a portion is shown here for guidance regarding its form and content.

2018, and references therein). In particular, Dambis et al. (2013) require that the stars in their sample have metallicity and distance estimates. This in general results in a global overrepresentation of intrinsically brighter stars. This overrepresentation may be negligible for nearby stars, but will become significant for the most distant stars which are predominantly metal-poor halo stars. On the contrary, we expect no selection effect in period except those that may arise as a consequence of indirect correlations with absolute magnitude.

This large sample of homogeneously distributed MW RRLs whose main characteristics span significantly large ranges in parameter space, in combination with the DR2 accurate parallaxes (see Fig. 1) allows us to study with unprecedented detail the infrared $PM$ and $PM2$, and the visual $MV$ – $[Fe/H]$ relations of RRLs (see Section 5).

3 COMPARISON WITH LITERATURE DATA

3.1 Comparison with previous parallax estimates in the literature

The lack of accurate trigonometric parallaxes for a significantly large sample of RRLs has been so far a main limitation hampering the use of RRLs as standard candles of the cosmic distance ladder. The ESA mission Hipparcos (van Leeuwen 2007 and references therein) has measured the trigonometric parallax of more than a hundred RRLs, however, for the vast majority of them the parallax uncertainty is larger than $\sim 30\%$. Trigonometric parallaxes measured with the Fine Guide Sensor (FGS) on board the HST have been published by Benedict et al. (2011) for only five MW RRLs: RZ Cep, SU Dra, UV Oct, XZ Cyg and RR Lyr itself. Finally, with Gaia DR1 in 2016 trigonometric parallaxes calculated as part of the TGAS were made available for 364 RRLs. In this section we compare the recently published Gaia DR2 parallaxes with the RRL parallax measurements available so far.

TGAS parallaxes are available in Gaia DR1 for 199 of the RRLs in our sample of 401. The blue histogram in Fig. 1 shows the distribution of uncertainties of the TGAS parallaxes for these 199 RRLs. The reduced uncertainty of the DR2 parallaxes (red histogram) with respect to TGAS is impressive. A direct comparison between DR2 and TGAS parallax values for the sample of 199 RRLs for which both parallax estimates are available is shown in Fig. 4. The DR2 parallaxes are generally in good agreement with the TGAS estimates, except for RR Lyr itself. The DR2 parallax of RR Lyr has a large negative value and deviates significantly from all other parallax estimates. The wrong DR2 parallax for RR Lyr was caused by an incorrect estimation of the star’s mean $G$ magnitude (17.04 mag, which is $\sim 10$ mag fainter than the star true magnitude), that induced an incorrect estimation of the magnitude-dependent term applied in the astrometric instrument calibration (Arenou et al. 2018, Gaia Collaboration et al. 2018).

A weighted least-squares fit of the relation $\pi_{TGAS} = \alpha \pi_{DR2}$ returns a slope $\alpha = 1.02 \pm 0.02$, which is close to the bisector line slope. However, there is a significant spread for $\pi_{DR2} \sim 0.3 - 1$ mas in Fig. 4, with the TGAS parallaxes having negative or significantly larger values than the DR2 parallaxes. Fig. 4 confirms the impressive reduction in the uncertainty of the DR2 parallax estimates compared to TGAS. The large uncertainties of the TGAS parallaxes prevent a reliable estimation of any zero-point offset that might exist between the DR2 and the TGAS parallaxes of RRLs.

Table 2 shows the comparison for five RRLs for which Hipparcos, HST, TGAS and Gaia DR2 parallax measurements are available. There is a general agreement between the HST, TGAS and DR2 parallaxes except for RR Lyr, whose DR2 parallax is clearly incorrect. Fig. 5 shows the Hipparcos (lower panel), HST (middle panel) and TGAS (upper panel) parallaxes plotted versus Gaia DR2 parallaxes for 4 of those 5 RRLs. For the sake of clarity we did not plot RR Lyr in the figure. Similarly to Fig. 4 the upper panel of Fig. 5 shows the nice agreement existing between TGAS and DR2 parallaxes. Agreement between Gaia DR2 and Hipparcos parallaxes (lower panel) is less pronounced; on the contrary, a very nice agreement between the HST and DR2 parallaxes is seen in the middle panel of Fig. 5, confirming the reliability of the Gaia DR2 parallaxes. However, the sample of RRLs with both, DR2 and HST parallax estimates available is too small to measure any possible zero-point offset of the Gaia parallaxes with respect to HST. The interested reader is referred to Arenou et al. (2018) who validated Gaia DR2 catalogue and found a negligible ($-0.01 \pm 0.02$ mas) offset between the HST and DR2 parallaxes using a sample of stars significantly larger than the few RRLs that could be used here.

3.2 Comparison of the $PL$ relations

Gaia Collaboration et al. (2017) in their figure 23 show the impressive improvement of $PMK_\ast$ relation of RRLs when going from the Hipparcos to the TGAS parallaxes. In this section we extend the comparison to the DR2 parallaxes. To
Table 2. Hipparcos, HST, TGAS and Gaia DR2 parallaxes of RRLs for which these independent measurements are available.

| Name     | \(\varpi_{\text{Hipparcos}}\) (mas) | \(\varpi_{\text{HST}}\) (mas) | \(\varpi_{\text{TGAS}}\) (mas) | \(\varpi_{\text{DR2}}\) (mas) |
|----------|--------------------------------------|-------------------------------|-------------------------------|-------------------------------|
| RR Lyr   | 3.46 ± 0.64                         | 3.77 ± 0.13                   | 3.64 ± 0.23                   | −2.61 ± 0.61                  |
| RZ Cep   | 0.59 ± 1.48                         | 2.12 ± 0.16                   | 1.43 ± 0.28                   | 1.40 ± 0.03                   |
| SU Dra   | 0.20 ± 1.13                         | 1.42 ± 0.16                   | 2.02 ± 0.22                   | 1.89 ± 0.03                   |
| UV Oct   | 2.44 ± 0.81                         | 1.71 ± 0.10                   | 1.56 ± 0.23                   | 1.57 ± 0.03                   |
| XZ Cyg   | 2.29 ± 0.84                         | 1.67 ± 0.17                   |                               |                               |

Figure 4. Comparison of the TGAS and DR2 parallaxes for 199 RRLs for which both parallax estimates are available. The solid line represents the bisector.

Figure 5. Comparison of the DR2 and TGAS (upper panel), DR2 and HST (middle panel), and DR2 and Hipparcos (lower panel) parallaxes for RRLs studied by Benedict et al. (2011) with the HST. RR Lyr has been omitted (see text for the details). The solid lines represent the bisectors.

In the present study allows us to avoid these issues as it is fully discussed in Section 4. However, only for visualisation purposes in this section we transformed the Hipparcos, TGAS and DR2 parallaxes in the corresponding absolute \(M_K\) magnitudes using Eq. 1.

\[ M = m_0 + 5\log \varpi - 10, \]

that links the star absolute magnitude \(M\) and its de-reddened apparent magnitude \(m_0\) to the star parallax in mas: \(\varpi\). Eq. 1 holds only for true (hence with formally zero or negligible uncertainties) absolute magnitudes, apparent magnitudes and parallaxes. However, the direct transformation of parallaxes to the absolute magnitudes as it is shown in Eq. 1 cannot be used for measured values that have non negligible uncertainties (Gaia Collaboration et al. 2017, Luri et al. 2018). This is because the direct inversion of the measured parallaxes to estimate the distance is well behaved in the limit of negligible uncertainties, but degrades quickly as the fractional uncertainty of the parallax grows, resulting in estimates with large biases and variances. Furthermore, negative parallaxes cannot be transformed into absolute magnitudes, thus an additional sample selection bias is introduced, since objects with the negative parallaxes must be removed from the sample. The Bayesian fitting approach we apply in the present study allows us to avoid these issues as it is fully discussed in Section 4. However, only for visualisation purposes in this section we transformed the Hipparcos, TGAS and DR2 parallaxes in the corresponding absolute \(M_K\), distances using Eq. 1. This transformation is possible only for 394, 195 and 96 RRLs in our sample, for which positive parallaxes in the DR2, TGAS and Hipparcos catalogues, respectively, are available. The corresponding \(PM_K\) distributions are shown in Fig. 6, that were obtained by correcting the apparent \(K\) mean magnitudes for extinction and after “fundamentalizing” the RRc stars by adding 0.127 to the logarithm of the period. The \(PM_K\) distribution in the upper panel of Fig. 6 shows the significant improvement of the DR2 parallaxes with respect to the TGAS (middle panel) and Hipparcos (lower panel) measurements.

3.3 Comparison with Baade-Wesselink studies

In this section we compare the DR2 trigonometric parallaxes with photometric parallaxes inferred from the Baade-
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Figure 6. RRL $P_M_{Ks}$ distributions obtained inferring the absolute magnitudes in the $K_s$-band ($M_{Ks}$) by direct transformation of the Gaia DR2 (upper panel), TGAS (middle panel) and Hipparcos (lower panel) parallaxes using Eq. 1. The period is measured in days.

Figure 7. Comparison of the photometric parallaxes inferred from $M_V$ (upper panel) and $M_K$ (bottom panel) absolute magnitudes estimated via BW method and the corresponding DR2 parallaxes for 23 MW RRLs for which both parallax estimates are available. The solid lines represent the bisectors.

Wesselink (BW) technique, which are available for some of the RRLs in our sample. Muraveva et al. (2015) summarise in their table 2 the absolute visual ($M_V$) and $K$-band ($M_K$) magnitudes obtained from the BW studies (Cacciari et al. 1992, Skillen et al. 1993, Fernley et al. 1998 and references therein) for 23 MW RRLs. The BW absolute magnitudes were revised assuming the value 1.38 (Fernley 1994) for the $p$ factor used to transform the observed radial velocity to true pulsation velocity and averaging multiple determinations for individual stars. All 23 RRL variables with absolute magnitudes estimated via BW technique have a counterpart in our sample of 401 RRLs. The comparison of the photometric parallaxes inferred from the BW $M_V$ and $M_K$ absolute magnitudes and the corresponding Gaia DR2 parallaxes for these 23 RRLs is shown in the upper and bottom panels of Fig.7, respectively. A weighted least squares fit of the relations $\varpi_{M_V(BW)} = \alpha \varpi_{DR2}$ and $\varpi_{M_K(BW)} = \alpha \varpi_{DR2}$ returns the same slope value of 1.06, which is close to the bisector slope $\alpha = 1$. Even though the DR2 parallaxes of these 23 RRLs are generally in good agreement with the photometric parallaxes obtained in the BW studies, we notice that there is a systematic difference between the two sets of parallaxes. Specifically, the mean non-weighted differences $\Delta \varpi_0 = \varpi_{DR2} - \varpi_{M_V(BW)}$ and $\Delta \varpi_0 = \varpi_{DR2} - \varpi_{M_K(BW)}$ are both equal to $-0.07$ mas. That is, the Gaia DR2 parallaxes for these 23 RRLs seem to be generally smaller than the photometric parallaxes inferred from the BW studies. However, in the parallax offset estimate we used the direct transformation of the absolute magnitudes to parallaxes and assumed symmetric Gaussian uncertainties for the sake of simplicity. Hence, the resulting parallax offset ($-0.07$ mas) may be affected by the asymmetry in the uncertainties. We perform a more careful analysis of the potential Gaia DR2 parallax offset for RRLs and discuss it in Section 5.2.

4 METHOD

4.1 Description of the Bayesian approach

In Delgado et al. (2018) we presented a Bayesian hierarchical method to infer the $PM$ and $PMZ$ relationships. The hierarchical models were validated with semi-synthetic data and applied to the sample of 200 RRLs described in Gaia Collaboration et al. (2017). Simplified versions of these models were also used in Gaia Collaboration et al. (2017). A full description of these models is beyond the scope of this manuscript and we recommend the interested reader to consult Delgado et al. (2018) for a more in-depth description of them. In what follows, we summarize what we consider are the minimum details about the hierarchical Bayesian methodology and our models necessary to understand the present paper as a self-contained study.

The core of the hierarchical Bayesian methodology consists of partitioning the parameter space associated to the problem into several hierarchical levels of statistical variability. Once this partition is done, the modeling process assigns probabilistic conditional dependency relationships between parameters at the same or different levels of the hierarchy. The construction of the model is finished when one is able to express a joint probability function of all the parameters of the model which factorizes as a product of conditional probability distributions. This factorization defines a
Bayesian network (Pearl 1988; Lauritzen 1996) consisting of a Directed Acyclic Graph (DAG) in which nodes encode model parameters and directed links represent conditional probability dependence relationships.

All models presented in Delgado et al. (2018) have three-level hierarchies. In all of them we partition the parameter space into measurements ($D$), true astrophysical parameters ($\Theta$) and hyperparameters ($\Phi$). In this case, the joint probability distribution associated to our models is given by

$$p(D, \Theta, \Phi) = p(D | \Theta) \cdot p(\Theta | \Phi) \cdot p(\Phi) \; ,$$

where $p(D | \Theta)$ is the conditional distribution of the data given the parameters (the so called likelihood), $p(\Theta | \Phi)$ is the prior distribution of the true parameters given the hyperparameters and $p(\Phi)$ is the unconditional hyperprior distribution of the hyperparameters. Bayesian inference is based on Bayes’ rule:

$$p(\Theta, \Phi | D) \propto p(D | \Theta) \cdot p(\Theta | \Phi) \cdot p(\Phi) \; ,$$

and its goal is to infer the marginal posterior distribution $p(\Lambda | D)$ of some subset $[\Lambda \subseteq (\Theta, \Phi)]$ of the parameters of interest. For the statistical inference problem of calibrating the RRL fundamental relationships, in this paper we primarily focus on inferring the parameters of such relationships. However, we also aim at getting insight on the true posterior distribution of Gaia DR2 parallaxes given their measured values.

In Figure 8 we present the generic DAG that encodes the probabilistic relationships between the parameters of all the models applied in this paper. The graph is intended to represent several models at once. For example, for a model devoted to infer a $PM$ relation, the nodes depicted with dimmer colours and their corresponding arcs do not belong to the model and the reader should not consider them. The DAG of Fig. 8 shows the measurements at the bottom level as blue nodes: decadic logarithm of periods $\log \hat{P}_i$, apparent magnitudes $\hat{m}_i$, metallicities $[\text{Fe/H}]_i$, parallaxes $\hat{\varpi}_i$, and extinctions $\hat{A}_m$. The subindex $i$ runs from 1 to the total number of stars $N$ in the sample. For each measurement there is a corresponding true value in the DAG. True values are represented as measurements but without the circumspect accent (‘†’) and are depicted by grey nodes. The model assumes that all measurements are realizations from normal distributions centered at the true (unknown) values and with standard deviations given by the measurement uncertainties provided by each catalogue. Note that true values and measurements are enclosed in a black rectangle that represents sample replication for $i = 1, 2, ..., N$ (plate notation). The model also takes into account the effect of the interstellar absorption when generating the measured apparent magnitudes from the true ones. So, it distinguishes between true (unabsorbed) apparent magnitudes $m_{0i}$ and true (absorbed) apparent magnitudes $m_i$ and deterministically computes the latter ones as $m_i = m_{0i} + A_{m, i}$, where $A_{m, i}$ represents the true absorption. This deterministic dependency of absorbed on unabsorbed apparent magnitude and true extinction is represented by dashed arrows in the DAG.

Once we have explained how the model manages the interstellar absorption, we describe how it generates the true (unabsorbed) apparent magnitudes $m_{0i}$ from true parallaxes $\hat{\varpi}_i$ and absolute magnitudes $M_i$. This is done by means of the deterministic relationship, coming from Eq. 1:

$$m_{0i} = M_i - 5 \log(\hat{\varpi}_i) + 10 \; ,$$

which is represented in the DAG by the dashed arcs going from $\varpi_i$ and $M_i$ to $m_{0i}$. The model also contemplates the existence of a Gaia global parallax offset $\varpi_0$ as suggested by Arenou et al. (2018). This offset can be inferred by the model itself or fixed to a predefined value.

The central core of the model is the submodel for the $PMZ$ relation in which absolute magnitudes $M_i$ are parameterized by

$$M_i \sim N(b + c \cdot \log \hat{P}_i + k \cdot [\text{Fe/H}]_i, w) \; ,$$

where $\sim$ should be read as ‘is distributed as’ and $N$ represents the normal (Gaussian) distribution. The mean of this normal distribution is a linear model in three parameters: the intercept $b$, the slope $c$ for the period term (in decadic logarithmic scale), and the slope $k$ for the metallicity term, and its standard deviation $w$ represents the linear model intrinsic dispersion. This intrinsic dispersion aims at including all potential effects not accounted for explicitly in the model (e.g. evolutionary effects). The dependency of absolute magnitude on the linear model parameters, intrinsic dispersion and predictive variables is represented in the DAG by all the incoming arrows to the node $M_i$.

For the slopes $c$ and $k$ of the $PMZ$ relationship of Eq. 5 we specify weakly informative Student’s $t$-priors with location parameter $\mu_c = \mu_k = 0$, and for the intercept we use a vague Gaussian prior centred at $\mu_b = 0$. The intrinsic dispersion of the $PMZ$ relation is given an exponential prior with inverse scale $\lambda_w = 1$. We use green rectangular
nodes at the top of the graph to denote all these fixed prior hyperparameters.

In Delgado et al. (2018) we reported the existence of a systematic correlation between measured periods, metallicities and parallaxes in our sample. This correlation occurred in the sense that a slight decrease of the median parallax and the median metallicity.

argue that this steep slope may be due to an offset affecting the DR2 parallaxes. However, we first check here whether the high metallicity dependence is not caused by a flaw in our Bayesian procedure. To this end we carried out simulations with semi-synthetic data. The semi-synthetic data were created according to the following recipe:

- we generated true metallicities drawn from Gaussian distributions (one for each star) centred at the measured values and with standard deviations given by the uncertainties described in Section 2;
- absolute magnitudes $M_V$ were derived from the true metallicities generated above using the $M_V - [\text{Fe/H}]$ relationship by Federici et al. (2012): $M_V = 0.25 [\text{Fe/H} + 0.89]$;
- true de-reddened apparent magnitudes were generated from Gaussian distributions centred at the observed values and with standard deviations given by the measurement uncertainties corrected for $V$-band extinctions generated likewise centred at the values in Dambis et al. (2013) and assuming an extinction uncertainty of 0.05 mag, as discussed in Section 2;
- finally, the true parallaxes were derived from the true absolute and apparent magnitudes, and the measured parallaxes were drawn from Gaussian distributions centred at the true values with standard deviations given by the Gaia DR2 parallax uncertainty of each star.

Our aim is to evaluate the capability of our methodology to recover unbiased estimates of the true parameters, in particular of the relationship slope. We infer posterior distributions of the model parameters for 10 realisations of the semi-synthetic data. The inferred slopes range between 0.251 and 0.254 mag/dex with a mean of 0.253 mag/dex (the true value used in the generation of the data being 0.25) with a constant credible interval of ±0.05. This represents a very mild overestimation of the true slope which could be due to the imperfection of the assumed priors. We have also applied models with a prior for the parallax that is independent of the period. As discussed in Delgado et al. (2018), this neglects the existence of a correlation between parallax and period in our sample and, as expected, results in slopes that are systematically biased (yielding an average slope from 10 random realisations of the semi-synthetic data set of 0.31 mag/dex and a posterior standard deviation of 0.05). In summary, we find that the Bayesian model designed and applied to the data is not the cause for the slopes being higher than expected according to the previous studies.

The steeper slope found by our methodology can be explained by considering the methodology applied when it is claimed in the literature that the fit was a weighted linear least-squares model with un-
parallaxes, we obtain a slope value of...than obtained from the whole sample of 381 RRLs, that may be the effect of using more accurate and homogeneous spectroscopic metallicities, and yet is still steeper than found in the more recent literature, even though (marginal) agreement exists within the uncertainties. A clue to further investigate the metallicity dependence issue may be to study the $M_V - \text{[Fe/H]}$ relation defined by large samples of RRLs in globular clusters for which the metallicity is well known from high resolution spectroscopic studies. This is addressed in a following paper (Garofalo et al., in preparation). Meanwhile, in Section 5.2 we examine whether the existence of a zero-point offset in the Gaia DR2 parallaxes (Arenou et al. 2018) might contribute to produce the high slope we find for the RRL $M_V - \text{[Fe/H]}$ relation.

5.2 Gaia DR2 parallax offset

The Gaia DR2 parallaxes are known to be affected by an overall zero-point whose extent varies depending on the sample used to estimate its value and, typically, is of the order of $-0.03$ mas, as estimated by comparison with QSO parallaxes (Arenou et al. 2018). After Gaia DR2 a number of studies have appeared in the literature (Riess et al. 2018; Zinn et al.; Stassun & Torres 2018) all suggesting that Gaia provides smaller parallaxes, hence, larger distance estimates, than derived from other independent techniques, that is, $\Delta \varpi_0 = \varpi_{\text{Gaia DR2}} - \varpi_{\text{indep}}$ is negative, but by how much varies from one study to the other. For instance, Riess et al. (2018) estimated a zero-point offset for Gaia DR2 parallaxes of $-0.046$ mas, combining HST photometry and Gaia DR2 parallaxes for a sample of 50 Cepheids. In the paper describing the final validation of all data products published in Gaia DR2, Arenou et al. (2018) estimate an offset $\Delta \varpi_0 = -0.056 \pm 0.005$ mas for RRLs in the Gaia DR2 catalogue and $-0.033 \pm 0.009$ mas for a sample of RRLs in the GCCVS. In the following we investigate whether the zero-point offset of the Gaia DR2 parallaxes for RRLs can affect the slope and zero-point inferred for their $M_V - \text{[Fe/H]}$ relation. We remind the reader that the non-linear relationship

| No. stars | $\alpha$ | $\beta$ | $\omega$ | $\Delta \varpi_0$ |
|-----------|---------|--------|---------|----------------|
| 381       | $0.48^{+0.05}_{-0.05}$ | $1.09^{+0.07}_{-0.07}$ | $0.24^{+0.02}_{-0.02}$ | 0.00 |
| 23        | $0.2^{+0.07}_{-0.07}$ | $0.1^{+0.10}_{-0.10}$ | $0.15^{+0.06}_{-0.05}$ | 0.00 |
| 23        | $0.2^{+0.07}_{-0.07}$ | $1.0^{+0.09}_{-0.09}$ | $0.1^{+0.03}_{-0.03}$ | 0.00 |
| 23        | $0.2^{+0.07}_{-0.07}$ | $1.0^{+0.09}_{-0.09}$ | $0.1^{+0.04}_{-0.04}$ | 0.00 |
between parallax and absolute magnitude (Eq. 1) implies that a given parallax offset does not affect all absolute magnitudes equally. Just for illustration purposes, a parallax offset of $-0.056$ mas as suggested by Arenou et al. (2018) for the RRLs would result in a change of the distance modulus equal to $0.2$ mag at $1$ kpc, while at $7$ kpc it would amount to $1.1$ mag. We are located in a relatively metal-rich area of the MW, while farther RRLs in our sample belong to the halo and likely are more metal-poor. Thus, the negative zero-point offset in the DR2 parallaxes will make farther/metal-poor RRLs to appear intrinsically brighter, hence causing an overestimation of the $M_V - [\text{Fe/H}]$ relation slope. Therefore, our discussion of the results must incorporate the effect of potential parallax offsets. The upper portion of Table 3 lists inference results for a series of linear $M_V - [\text{Fe/H}]$ models characterised by different parallax offsets, namely, models without offset, with a global offset of $-0.03$ mas (Arenou et al. 2018) and with an offset of $-0.07$ mas, as suggested by the comparison with the absolute magnitudes derived from the BW studies (Section 3.3). Results of this test show that it is of crucial importance to take into account a potential parallax offset when studying the RRL $M_V - [\text{Fe/H}]$ relation because the slope of the relation varies with the offset and decreases systematically with increasing offset from $\alpha = 0.48$ (no offset), to $\alpha = 0.36$ for an offset of $-0.07$ mas. We applied the same model to the 23 MW RRLs with homogeneous metallicity estimates based on abundance analysis of high-resolution spectra (see Section 5.1), assuming no parallax offset and the offsets of $-0.03$ mas and $-0.07$ mas. The resulting solutions are shown in the lower portion of Table 3. The slope of the $M_V - [\text{Fe/H}]$ relation varies from $0.29 \pm 0.07$ (no offset) to $0.28 \pm 0.07$ mag/dex (offset of $-0.07$ mas), showing that for the sample of 23 RRLs, with both distances and range of distances much smaller than for the full sample, the impact of a potential parallax offset on the slope of the $M_V - [\text{Fe/H}]$ relation is greatly reduced.

To compute all the relationships presented in this paper we use the model that includes the potential parallax offset as a parameter (Section 4). We fitted the $M_V - [\text{Fe/H}]$ relation defined by the whole sample of RRLs inferring simultaneously the relation parameters (slope and zero-point) and the parallax offset. Corresponding results are summarised in the upper portion of Table 4 (first row). From our sample of 381 RRLs we obtain a mean posterior metallicity slope of 0.38 for a mean posterior offset of $-0.056$ mas (unsurprisingly equal to the offset reported by Arenou et al. 2018 for RRLs). The resulting $M_V - [\text{Fe/H}]$ fit is shown in Fig. 11, where colours encode the (natural) logarithm of the inferred distance.

We applied the same model to the 23 MW RRLs with homogeneous metallicity estimates. The resulting $M_V - [\text{Fe/H}]$ relation is shown in middle panel of Table 4. In the case of the 23 MW RRLs, the reduced number of measurements and the smaller range of distances (visible from the colour scale in Fig. 12) does not constrain the value of the offset. The first row of the middle portion of Table 4 summarises the posterior distribution for the offset with a mean of $-0.146^{+0.07}_{-0.08}$ which seems implausible. This translates directly into a much smaller metallicity slope of 0.26 ± 0.7 mag/dex compared to the one inferred for the 381 stars sample. If we remove the determination of the parallax offset as a parameter of the model and, instead, adopt a constant value for the offset of $-0.056$ mas, we obtain a slope of 0.28 ± 0.07 for the sample of 23 RRLs. The resulting $M_V - [\text{Fe/H}]$ relation is shown in the lower portion of Table 4. Hence, although the credible intervals for the slopes derived from the two samples (381 and 23 stars) overlap (especially for an offset of $-0.056$), the discrepancy exists, owing to (i) a small effect of the parallax offset on a sample of 23 nearby stars; (ii) a more accurate estimation of metallicity based on high-resolution spectroscopy for 23 RRLs. At the same time we must also stress that selection effects can potentially be stronger as only nearby bright RRLs are characterised by high enough signal-to-noise ratios to be analysed with high-resolution spectroscopy.

Since a number of theoretical studies suggest a nonlinear $M_V - [\text{Fe/H}]$ relation, we have also explored quadratic relationships between $M_V$ and $[\text{Fe/H}]$. Table 4 includes a summary of the posterior distributions of selected model parameters. In the two cases (381 and 23 RRL samples), the effect of including a second order term is to increase the mean value of the first order term posterior distribution from 0.38 to 0.45 (sample of 381 stars) and from 0.26 to 0.40 (sample of 23 stars). We mentioned above that there is a controversy relative to the nature (linear or quadratic) of the relationship between metallicity and absolute magnitudes. We have therefore attempted to assess the relative merit of the two models (linear and quadratic) in the light of the available data. In doing so, we are limited by the sampling scheme chosen (Hamiltonian Monte Carlo as implemented in OpenBUGS; Carpenter et al. 2017). Given this implementation, we cannot use evidences or Bayes’ factors and resort to the Bayesian leave-one-out estimate of the expected log-pointwise predictive density (Vehtari, Gelman & Gabry 2017). The comparison of the values obtained for the two models is inconclusive: the mean value of the paired differences is $-4.4 \pm 8.8$ favouring the more complex (quadratic) model but with no statistical significance. The quadratic $M_V - [\text{Fe/H}]$ relations for 381 and 23 MW RRLs are shown in Figs. 13 and 14, respectively.
Table 4. RRL MZ and PMZ relations based on Gaia DR2 parallaxes.

| No. stars | Relation | $w$ (mag) | $\Delta x_0$ (mas) | $\rho_{LMC}$ (mag) |
|-----------|----------|------------|-------------------|-------------------|
| Lin. $M_V - [\text{Fe/H}]$ | 381 | $M_V = (3.83 \pm 0.07) [\text{Fe/H}] + (1.16 \pm 0.07) \log (P) + (0.18 \pm 0.07) [\text{Fe/H}] + (1.21 \pm 0.11)$ | $0.29 \pm 0.02$ | $-0.056 \pm 0.01$ | $18.54 \pm 0.16$ |
| Quad. $M_V - [\text{Fe/H}]$ | 381 | $M_V = (3.94 \pm 0.09) [\text{Fe/H}]^2 + (0.45 \pm 0.16) [\text{Fe/H}] + (1.21 \pm 0.11)$ | $0.23 \pm 0.02$ | $-0.057 \pm 0.01$ | $18.53 \pm 0.16$ |
| $PM_{K}\_Z$ | 396 | $M_{K_\alpha} = -2.44 \pm 0.35 [\text{Fe/H}] + 0.18 \pm 0.07 [\text{Fe/H}] + (0.18 \pm 0.10) [\text{Fe/H}] + (0.12 \pm 0.10)$ | $0.25 \pm 0.02$ | $-0.051 \pm 0.01$ | $18.57 \pm 0.11$ |
| $PM_{W1}\_Z$ | 397 | $M_{W1} = -2.40 \pm 0.35 [\text{Fe/H}] + 0.18 \pm 0.07 [\text{Fe/H}] + (0.11 \pm 0.10)$ | $0.24 \pm 0.02$ | $-0.051 \pm 0.01$ | $18.57 \pm 0.11$ |

Lin. $M_V - [\text{Fe/H}]$ | 23 | $M_V = (0.26 \pm 0.07) [\text{Fe/H}] + (1.15 \pm 0.13)$ | $0.14 \pm 0.04$ | $-0.146 \pm 0.07$ | $18.35 \pm 0.16$ |
| Quad. $M_V - [\text{Fe/H}]$ | 23 | $M_V = (0.06 \pm 0.09) [\text{Fe/H}]^2 + (0.40 \pm 0.22) [\text{Fe/H}] + (1.20 \pm 0.16)$ | $0.14 \pm 0.04$ | $-0.127 \pm 0.08$ | $18.40 \pm 0.15$ |
| $PM_{K}\_Z$ | 23 | $M_{K_\alpha} = -2.58 \pm 0.69 [\text{Fe/H}] + 0.12 \pm 0.10 [\text{Fe/H}] + (0.10 \pm 0.10)$ | $0.14 \pm 0.04$ | $-0.137 \pm 0.08$ | $18.41 \pm 0.10$ |
| $PM_{W1}\_Z$ | 23 | $M_{W1} = -2.66 \pm 0.81 \log (P) + (0.09 \pm 0.10)$ | $0.14 \pm 0.04$ | $-0.142 \pm 0.07$ | $18.51 \pm 0.15$ |

Figure 10. Distribution in apparent $V$ magnitude (upper panel), period (middle panel) and metallicity (as derived from high-resolution spectroscopy; lower panel) for the 23 RRLs in Fig. 9.

5.3 Infrared PMZ relations

A number of studies on the RRL near-infrared $PM_K$ and $PM_K Z$ relations exist in the literature both from the empirical (e.g. Longmore et al. 1986; Dall’Ora et al. 2004; Del Principe et al. 2006; Sollima et al. 2006; Borissova et al. 2009; Muraveva et al. 2015; Gaia Collaboration et al. 2017) and the theoretical (e.g. Bono et al. 2003; Catelan et al. 2004; Marconi et al. 2015) points of view. While empirical studies suggest a mild or even negligible dependence of the $K$-band luminosity on metallicity, the theoretical studies find for the metallicity term of the $PM_K Z$ relation slope values up to $0.251 \pm 0.012$ (Bono et al. 2003). The literature values for the dependence of the $M_K$ magnitude on period also vary ranging from $-2.101$ (Bono et al. 2003) to $-2.73 \pm 0.25$ (see table 3 in Muraveva et al. 2015, for a compilation).

The mid-infrared $PM_{W1}$ and $PM_{W1} Z$ relations are even more promising tools for the purpose of establishing the distance ladder with RRLs, because of the lower sensitivity of the mid-infrared luminosities to interstellar extinction, than at optical and near-infrared wavelengths. The
RRL mid-infrared relations at the $W1$ (3.4 $\mu$m) passband of WISE, $PM_{W1}$ and $PM_{W1}Z$, have also been studied from many different authors both from empirical (e.g. Madore et al. 2013; Dambis et al. 2014; Klein et al. 2014; Neeley et al. 2015, Sesar et al. 2017, Gaia Collaboration et al. 2017) and theoretical (e.g. Neeley et al. 2017) grounds, with theoretical studies suggesting a non-negligible dependence on metallicity of $0.180 \pm 0.003$ mag/dex, (Neeley et al. 2017). For comparison, Dambis et al. (2014) derived a dependence on metallicity of $0.096 \pm 0.021$ mag/dex of the $PM_{W1}Z$ relation, from their studies of RRls in globular clusters, while Sesar et al. (2017) derived a metallicity slope of $0.15^{+0.09}_{-0.08}$ mag/dex using TGAS parallaxes for a sample of about a hundred MW RRls. The literature values of the period slope vary from $-2.251 \pm 0.018$ (3.6 $\mu$m passband; Neeley et al. 2017) to $-2.440 \pm 0.950$ (Madore et al. 2013, based on only 4 RRls with HST parallaxes from Benedict et al. 2011).

We derived infrared $PM_{K_s}Z$ and $PM_{W1}Z$ relations for the RRls in our sample using the Bayesian approach described in Section 4 and inferring the parallax zero-point offset from the model. The near-infrared $PM_{K_s}Z$ relation is based on a sample of 396 RRls for which all needed information along with apparent $K_s$ magnitudes and related uncertainties are available in Dambis et al. (2013) (see Sect. 2). To derive the $PM_{W1}Z$ relation we used a sample of 397 RRls for which $W1$ magnitudes and related uncertainties are also available in Dambis et al. (2013). The coefficients of the resulting relations are summarised in the upper section of Table 4 (row 3 and 4 respectively) and graphically shown in Figs. 15 and 16, where the colours encode the RR metallicitics on the Zinn & West (1984) metallicity scale.
inferred the parallax offset as a parameter of the model and period of the studies but in excellent agreement with the theoretical find-

The slope in period we derive for the $PM_KZ$ relation is in perfect agreement with the literature values, while the metallicity slope is higher than found in previous empirical studies but in excellent agreement with the theoretical find-
ings (e.g. Bono et al. 2003, Catelan et al. 2004). The slope in period of the $PM_{K1}Z$ relation is also in a good agreement with the literature values and we also find a non-negligible metallicity dependence, that is consistent with results from Neeley et al. (2017) and Sesar et al. (2017). We have performed the fitting on our reduced sample of 23 RRLs both infering the parallax offset as a parameter of the model and assuming a constant offset value of −0.056 mas. The resulting relations are presented in the middle and lower portions of Table 4. Figs. 17 and 18 graphically show the $PM_KZ$ and $PM_{K1}Z$ relations obtained from this reduced sample of 23 MW RRLs, when inferring the parallax offset as a parameter of the model. As with the RRL $M_V−[Fe/H]$ relation the metallicity slope is significantly shallower for the reduced sample of 23 RRLs and in agreement within the uncertainties with values presented in the literature (e.g. Bono et al. 2003, Catelan et al. 2004, Neeley et al. 2017, Sesar et al. 2017).

6 DISTANCE TO THE LMC

As traditionally done in this type of studies, in order to test the Gaia DR2 parallax-calibrated relations of RRLs derived in Section 5 we apply them to infer the distance to the LMC, a cornerstone of the cosmological distance ladder, whose distance has been measured in countless studies with different distance indicators and independent techniques (see e.g. Gibson 2000; Benedict et al. 2002; Clementini et al. 2003; and de Grijs et al. 2014 for compilation of the values in the literature). The vast majority of the literature estimates agree on a value of $\mu_{LMC} = 18.49 \pm 0.09$ mag, which is in excellent agreement with the value of $\mu = 18.493 \pm 0.008$(stat) $\pm 0.047$(syst) mag inferred by Pietrzyński et al. (2013) from the analysis of eight eclipsing binaries in the LMC bar. Following Gaia Collaboration et al. (2017), we considered a sample of 70 RRLs located close to the LMC bar, for which spectroscopically measured metallicities (Gratton et al. 2004), extinction, periods and photometry in the V (Clementini et al. 2003) and $K_s$ (Muraveva et al. 2015) bands, are available. No $W1$-band photometry is available for these 70 LMC RRLs, while $V$-band is available only for 62 of them. We applied the linear and quadratic $M_V−[Fe/H]$ relations and the $PM_KZ$ relations presented in Table 4, to infer the distance to each RRL individually and then computed the weighted mean of the distribution. The metallicity scale adopted by Gratton et al. (2004), is 0.06 dex more metal-rich than the Zinn & West (1984) metallicity scale. We subtracted 0.06 dex from the metallicities of the LMC RRLs to convert them to the Zinn & West (1984) metallicity scale when dealing with the relations based on the whole sample.

Figure 16. $PM_{K1}$ distribution of 397 RRLs from our sample, for which absolute $M_{K1}$ magnitudes were inferred from the model described in Section 4. The lines represent projections of the fit shown in the upper portion of Table 4 onto the Magnitude-Period plane. The colour scale encodes values of measured metallicity on the Zinn & West (1984) metallicity scale.

Figure 17. $PM_{K1}$ distribution of 23 RRLs from our sample, for which absolute $M_{K1}$ magnitudes were inferred from the model described in Section 4. The lines represent projections of the fit shown in the middle portion of Table 4 onto the Magnitude-Period plane. The colour scale encodes values of measured metallicity on the high-resolution spectroscopy metallicity scale.

Figure 18. $PM_{K1}$ distribution of 23 RRLs from our sample, for which absolute $M_{K1}$ magnitudes were inferred from the model described in Section 4. The lines represent projections of the fit shown in the middle portion of Table 4 onto the Magnitude-Period plane. The colour scale encodes values of measured metallicity on the high-resolution spectroscopy metallicity scale.
of RRLs. No correction was applied instead when using the relations based on the 23 MW RRLs with metal abundances obtained from high-resolution spectroscopy. The LMC distance moduli obtained with this procedure are summarised in the last column of Table 4 and shown in Fig. 19. They all agree within 1σ uncertainty (grey dashed lines) with the canonical value of 18.49 mag (grey solid line). However, it is clear from Fig. 19 that distance moduli obtained using relations for the 23 MW RRLs and the parallax offset inferred from the model are systematically shorter. This is expected, because, as discussed in Section 5.2, the parallax offset inferred from the 23 RRLs is significantly overestimated by the model, hence, correcting for it causes smaller distances. And in fact, the relations based on the sample of 23 MW RRLs and an assumed constant value of the parallax offset of −0.056 mas (green triangles) is in very good agreement with the canonical value of the LMC distance modulus. To conclude, the LMC distance moduli obtained in this study using the Gaia DR2 parallaxes are in good agreement with the canonical value, once the Gaia DR2 parallax offset is properly accounted for.

7 SUMMARY AND CONCLUSIONS

Gaia Data Release 2 provides accurate parallaxes for an unprecedented, large number of MW RRLs. In this study we analysed a sample of 401 MW field RRLs, for which $V$, $K_s$, and $W1$ photometry, metal abundances, extinction values and pulsation periods are available in the literature and accurate parallaxes have become available with the Gaia DR2. We compared the Gaia DR2 parallaxes with the parallax estimates for these RRLs available in the Hipparcos, HST and TGAS catalogues. We find a general good agreement of the Gaia DR2 parallaxes with the TGAS and the HST measurements, while agreement with the Hipparcos catalogue is less pronounced. The accuracy of the DR2 parallax measurements for RRLs showcases an impressive improvement achieved by Gaia both with respect to its predecessor Hipparcos and the TGAS measurements released in DR1, and rivals to other space-born estimates by cutting down about a factor of 5 the parallax uncertainty for RRLs measured with the HST. We compared the Gaia DR2 parallaxes with photometric parallaxes inferred from the BW studies of 23 MW RRLs and find a zero-point offset of −0.07 mas, with the Gaia DR2 parallaxes being systematically smaller.

With Gaia DR2 it is for the first time possible to determine the coefficients (slopes and zero-points) of the fundamental relations ($M_V - [Fe/H]$, $PM_K$, $PM_{W1}$), that RRLs conform to on the basis of statistically significant samples, that we do in this paper by applying a fully Bayesian approach that properly handles parallax measurements and biases affecting our sample of 401 MW RRLs. We find the dependence of the luminosity on metallicity to be higher than usually adopted in the literature. We show that this high metallicity dependence is not caused by our inference method, but likely arises from the actual distribution of the parallaxes to establish the cosmic distance ladder by recovering the canonical value of 18.49 mag for the distance modulus of the Large Magellanic Cloud, once the DR2 parallax offset is properly corrected for. We hence confirm that Gaia is on the right path a look forward to DR3, which is currently foreseen for end of 2020.

ACKNOWLEDGEMENTS

This work makes use of data from the ESA mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. Support to this study has been provided by PRIN-INAF2014, dpac/consortium (DPAC, https://www.cosmos.esa.int/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. Support to this study has been provided by PRIN-INAF2014, dpac/consortium (DPAC, https://www.cosmos.esa.int/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. Support to this study has been provided by PRIN-INAF2014, dpac/consortium (DPAC, https://www.cosmos.esa.int/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. Support to this study has been provided by PRIN-INAF2014.
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