EVIDENCE FOR AN OVERLUMINOSITY OF THE VARIABLE STAR RR Lyr,
AND A REVISED DISTANCE TO THE LMC
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ABSTRACT

We use theoretical models to establish a tight relationship for the absolute magnitudes of RR Lyrae stars as a function of their periods and Strömgren pseudo-color $c_0 \equiv (u-v)_0 - (v-b)_0$. Applying this to RR Lyr, and comparing the result with the predicted average absolute magnitude for stars of similar metallicity from the same models, yields an over luminosity of $0.064 \pm 0.013$ mag in Strömgren $y$ (and thus similarly in $V$) for RR Lyr. Based on a revised value for RR Lyr’s trigonometric parallax, and on a newly derived reddening value of $E(B-V) = 0.015 \pm 0.020$, we provide a corrected relationship between average absolute magnitude and metallicity for RR Lyrae stars that takes RR Lyr’s evolutionary status fully into account for the first time. Applying this relationship to the LMC, we derive a revised true distance modulus of $(m-M)_0 = 18.44 \pm 0.11$.

Subject headings: stars: distances — stars: horizontal-branch — stars: variables: other — distance scale

1. INTRODUCTION

RR Lyrae (RRL) stars are radially pulsating variable stars with periods in the $0.2 - 1.0$ d range, and visual amplitudes $\leq 2$ mag. They are accordingly easily identified, and play a key role as the cornerstone of the Population II distance scale. They are extensively used to determine distances to old and sufficiently metal-poor systems, where they are commonly found in large numbers. In particular, RRL are present in globular clusters (GC’s) and the dwarf galaxies in the neighborhood of the Milky Way (e.g., Greco et al. 2007), and have also been identified in the M31 field (e.g., Brown et al. 2004; Dolphin et al. 2004), in some M31 companions (e.g., Pritzl et al. 2005), and in at least 4 M31 GC’s (Cacciari & Clementini 2003). Unfortunately, RR Lyr’s evolutionary status remains at present unknown, and therefore it is still unclear whether it is representative of the underlying stellar population to which it is associated. This is an important issue since, as can be seen from Figure 1, a scatter in the average HB absolute magnitude computed for a large sample of RRL stars in extensive HB simulations covering the full range of metallicities is still present (Benedict et al. 2002). This star has accordingly been used by several authors to place the zero point of the $(M_V - [Fe/H])$ relation on a firmer footing (e.g., Catelan 2005).

RRL-based distances are usually derived using a simple relation between average RRL $V$-band magnitude and metallicity. However, RR Lyr is the only RRL-type star with a sufficiently accurate trigonometric parallax for distance determinations (Benedict et al. 2002). This star has accordingly been used by several authors to place the zero point of the $(M_V - [Fe/H])$ relation on a firmer footing (e.g., Catelan 2005). Unfortunately, RR Lyr’s evolutionary status remains at present unknown, and therefore it is still unclear whether it is representative of the underlying stellar population to which it is associated. This is an important issue since, as can be seen from Figure 1, a scatter in the RRL magnitudes (by up to a few tenths of a magnitude; see also Sandage 1990) is always expected within any single population, and therefore distances based on current calibrations of the $(M_V - [Fe/H])$ relation may be correspondingly in error (e.g., Catelan 2005).

To emphasize this point, Figure 2 compares the difference in absolute magnitude between individual RRL stars in three HB simulations with widely different HB morphologies and the average HB absolute magnitude computed for a large sample of RRL stars in extensive HB simulations covering the full
range of observed HB morphologies (\langle M_y \rangle = 0.6614 \pm 0.0008 and median \bar{M}_y = 0.6896, based on 8114 synthetic stars).

Up to now, no method had been available to infer the evolutionary status of individual RRL stars to a precision better than 0.1 mag. The Strömgren system may provide us with a solution to this problem. In particular, Cortés & Catelan (2007) have shown that, by incorporating a pseudo-color term to the PL relation, exceedingly tight relations derive, even for the bluer bandpasses. We have thus used the sample of 8114 synthetic RRL stars mentioned above to search for high-precision analytical fits that would provide absolute magnitudes to a precision of \sim 0.01 mag. We thus found a linear dependence on log P and a cubic dependence on the (log of the) pseudo-color c_0. Our final relations thus read as follows:

\begin{equation} \label{eq:fits} M_{\text{band}} = a + b \ln c_0 + c (\ln c_0)^2 + d (\ln c_0)^3 + e \log P. \end{equation}

The coefficients of the fits for each of the four uvby bands, along with their respective errors, are given in Table 1. The correlation coefficient ranges from r = 0.992 to 0.998, and the standard errors of the estimates from 0.0072 to 0.0078 mag.

To check how well equation (1) is able to reproduce \text{M}_y for individual RRL stars, we show, in Figure 3, the difference between the \text{M}_y value implied by this equation and the input value from the same HB simulations as in Figure 2. As can be clearly seen, the scatter, which in the previous figure amounted to several tenths of a magnitude, has been reduced to a few thousandths of a magnitude only. It is thus clear that equation (1) is capable of providing \text{M}_y values for RRL stars with remarkable precision, provided of course their periods and c_0 values are known. Comparing this with \text{M}_y from the same models, one immediately obtains a robust estimate of the degree of overluminosity for individual RRL stars.

3. A NEW LOOK AT RR Lyr

Though RR Lyr is an extensively studied star, not many RRL surveys have been carried out in the Strömgren system to date – the papers by Epstein (1969) and Siegel (1982) being notable exceptions. We shall adopt the latter’s dataset in this work. Siegel carried out his uvby3 study of RR Lyr using the 16 in telescope at Kitt Peak, and provided a c_1 light curve. This is shown in Figure 2 where Siegel’s two datasets (representing two different phases in the star’s \sim 40 d-long Blazhko cycle) are displayed.

Naturally, in order to be able to apply our method to RR Lyr, we first need to compute a suitable average c_1 value for the star. In this sense, we have first carried out a Fourier fit to the star’s observed c_1 curve. The result of a 5th-order Fourier decomposition is also shown in Figure 4. Averaging over this curve in magnitude units, we find (c_1)_\text{mag} = 0.861 \pm 0.002. Performing the same average in intensity units, we obtain a slightly different result, namely (c_1)_I = 0.850 \pm 0.002. In like vein, \langle \mu \rangle - 2 \langle \nu \rangle + \langle b \rangle = 0.850 \pm 0.010. We have performed the

### Table 1

| Coefficient | Value | Error | Coefficient | Value | Error |
|-------------|-------|-------|-------------|-------|-------|
| a           | +1.8000 | 0.0010 | a           | +0.4355 | 0.0009 |
| b           | -1.1484 | 0.0029 | b           | -1.9103 | 0.0027 |
| c           | -0.4903 | 0.0213 | c           | -0.9250 | 0.0204 |
| d           | -1.3840 | 0.0463 | d           | -1.4128 | 0.0443 |
| e           | -1.7643 | 0.0026 | e           | -1.8575 | 0.0025 |
| a           | +0.1070 | 0.0009 | a           | -0.1244 | 0.0099 |
| b           | -1.6721 | 0.0027 | b           | -1.3546 | 0.0026 |
| c           | -0.8628 | 0.0197 | c           | -0.7413 | 0.0195 |
| d           | -1.2972 | 0.0430 | d           | -1.3146 | 0.0425 |
| e           | -1.9507 | 0.0024 | e           | -2.0577 | 0.0024 |
same test using Fourier decompositions of different orders, with no significant differences in the final average values. Likewise, the average $c_1$ value, as derived based on Siegel’s (1982) dataset 2 only, is not noticeably different from that provided above. (His dataset 1 is missing the minimum.) One of the main advantages of the present method is indeed the fact that the amplitude of the $c_1$ light curve is rather small ($0.52$ mag, according to the 5th-order Fourier fit), so that the differences between the several procedures to obtain the average quantities appear to be minor. We finally adopt for RR Lyr an average $c_1 = 0.855 \pm 0.005$.

As far as the reddening correction goes, we remind the reader that $c_1$ is a rather reddening-insensitive index, with $c_0 = c_1 - 0.15 E(B-V)$. The reddening of RR Lyr is not well determined. Sollima et al. (2008) have recently argued that a value $E(B-V) = 0.02 \pm 0.03$ safely covers all of the available determinations. An independent reddening determination is afforded by comparing the star’s Strömgren photometry and our relations (see eq. 1 and Table 1).

In this sense, we have computed magnitude- and intensity-averaged $B-y$, $v-b$, $u-v$, and $u-y$ colors for RR Lyr, and compared the values derived using Siegel’s (1982) combined dataset and his dataset 2 only. We then averaged the results, adopting as final average colors for RR Lyr the following values: $b-y = 0.282 \pm 0.002$, $u-v = 1.215 \pm 0.003$, $v-b = 0.357 \pm 0.002$, and $u-y = 1.857 \pm 0.009$. The error bars include the errors of the Fourier fits used to compute the means, as well as the dispersion around the mean value given by the different definitions of the “equivalent static star.” Comparing these values with the intrinsic colors implied by our theoretical relations at $c_0 = 0.855 \pm 0.005$ and a period $P = 0.5668386$ d (Kolenberg et al. 2006), using the relationships $E(b-y) = 0.74 E(B-V)$, $E(u-v) = 0.65 E(B-V)$, $E(v-b) = 0.50 E(B-V)$, and $E(u-b) = 1.89 E(B-V)$ (Crawford & Mandewewala 1976; Clem et al. 2004), and taking a weighted average over the thus derived individual $E(B-V)$ values, we find for RR Lyr a revised reddening value of

$$E(B-V) = 0.015 \pm 0.020,$$

which also implies a small correction to the adopted $c_0$ value for RR Lyr, which becomes $c_0 = 0.853 \pm 0.006$.

Inserting these values into equation (11) for $y$, we find $M_y = 0.585 \pm 0.010$ mag. Using the average $M_y$ for RRL stars of similar metallicity, from §2, we find that RR Lyr is an overluminous star, by about $0.077 \pm 0.010$ mag in $y$ (and thus $V$). The inferred position of the star is shown in the CMD of Figure 1 for an overluminosity in $y$ of zero to obtain, we would have needed a $c_0 = 0.801$ for RR Lyr, which is many sigma away from the value derived on the basis of Siegel’s (1982) data. Note that the star’s overluminosity, with respect to the median, is even higher: $0.105 \pm 0.010$ mag. We emphasize that this result is based on a differential use of the theoretical models. Within the error bars, RR Lyr’s overluminosity is also not inconsistent with the recent near-IR study by Sollima et al. (2008, their Fig. 2).

To check the model dependence of this result, we repeated our procedure using the Pietrinferni et al. (2004) tracks, corrected as in Cassisi et al. (2004). Based on the resulting HB simulations we rederive the parameters of equation (1), leading to a relation with $r = 0.993$ and standard error of the estimate $0.006$ mag. We infer the $M_y$ value for RR Lyr therefrom ($M_y = 0.580$ mag), and compare with the value ($M_y = 0.6576$ mag from the same simulations. This gives for RR Lyr an overluminosity of $0.077$ mag, in perfect agreement with the value derived earlier. Using the Lee & Demarque (1990) models for $Y_M = 0.23$, the overluminosity we find is $0.064$ mag, again consistent with our previous results.

Cortés & Catelan (2007) caution that a star’s exact overluminosity will depend on the adopted metallicity scale. To safely accommodate the resulting range of possible values for RR Lyr, we finally adopt for this star an overluminosity in $y$ (and thus $V$) of $0.064 \pm 0.013$ mag.

4. A REVISED RRL ($M_V$) $-$ [FE/H] RELATION

Let us assume, as often done, a relation of the form $(M_V) = \alpha [\text{Fe/H}] + \beta$. Here we shall adopt a slope $\alpha = 0.23 \pm 0.04$, as suggested in several recent reviews of the subject (e.g., Cassisi & Clementini 2003). What about the zero point $\beta$? Benedict et al. (2002) obtained, using the Hubble Space Telescope (HST), an accurate value for RR Lyr’s trigonometric parallax, namely $\pi_{\text{HST}} = 3.82 \pm 0.20$ mas. Very recently, van Leeuwen (2007) revised the trigonometric parallaxes provided by Hipparcos, and arrived at a value $\pi_{\text{abs}} = 3.46 \pm 0.64$ mas for RR Lyr. A weighted average of ground-based studies (van Altena, Lee, & Hoffleit 1995) indicates a parallax $\pi_{\text{ground}} = 3.0 \pm 1.9$ mas for this star. Taking a weighted average of these results, we obtain a final value of $\pi_{\text{abs}} = 3.78 \pm 0.19$ mas for RR Lyr. This implies a revised distance modulus of $(m-M)_0 = 7.11 \pm 0.11$ mag for the star.

In recent work, an intensity-weighted mean magnitude of $V = 7.76$ mag (Fernley et al. 1998, F98) has been adopted for RR Lyr. However, we note that this value is based on Hipparcos photometry, which may require a non-trivial transformation to the standard system. For comparison, Lavender (1994) determines a $V = 7.66$ mag, and Lavender et al. (1996) find instead $(V) = 7.74$ mag. Gould & Popowski (1998, GP98) argue strongly in favor of the Hipparcos-based magnitudes of F98, but propose a (small) reddening-related correction: $V_{\text{GP98}} = V_{\text{F98}} - 0.2 E(B-V)$. Using our derived reddening value (eq. 2), and adopting a standard extinction law with $A_V = 3.1 E(B-V)$, one finds $A_{\text{RR}} = 0.045 \pm 0.062$ mag. The final, extinction-corrected RR Lyr mean magnitude is accordingly $(V_0) = 7.710 \pm 0.062$ mag.

Footnote: To derive an overluminosity in other bandpasses is more tricky, in view of the non-zero slope of the HB in planes other than $M_y, b-y$. Taking the HB slope into due account, we find for RR Lyr overluminosities in $u, v, b$ of $-0.075, -0.113,$ and $-0.096$ mag, respectively.
As well known, the intensity- or magnitude-weighted mean magnitude does not necessarily correspond to the magnitude of the “equivalent static star” (i.e., the magnitude the star would have if it were not pulsating): an amplitude-dependent correction has to be applied. Such a correction has been obtained by Bono, Caputo, & Stellingwerf (1995) on the basis of detailed hydrodynamical models. Inspection of the light curves for RR Lyr (e.g., Szeidl & Kollath 2000; Smith et al. 2003; Kolenberg et al. 2004) suggests that the amplitude in V oscillates in the 0.5–1.1 mag range. According to Table 2 in Bono et al., this is precisely the amplitude range over which the intensity-weighted mean magnitude provides the most accurate description of the magnitude of the equivalent static star. Taking, accordingly, a value \( \langle \mathcal{V}_0 \rangle = 7.710 \pm 0.062 \) mag and a distance modulus \( (m-M)_0 = 7.11 \pm 0.11 \) mag, one finds an absolute magnitude for the star of \( M_V = 0.600 \pm 0.126 \) mag.

This, as previously argued, should not be viewed as representative of the average absolute magnitude of RRL stars of similar metallicity: according to our results, the latter are fainter (on average) than RRL by about 0.064 ± 0.013 mag. Therefore, the average absolute magnitude of RRL stars of metallicity similar to RR Lyr’s should be

\[
\langle M_V \rangle = 0.664 \pm 0.127 \text{ mag.} \tag{3}
\]

Adopting for RR Lyr the metallicity values provided in §2, one then finds the following final relations:

\[
\langle M_V \rangle = (0.23 \pm 0.04)[{\rm Fe/H}]_{ZW84} + (0.984 \pm 0.127), \tag{4a}
\]

\[
\langle M_V \rangle = (0.23 \pm 0.04)[{\rm Fe/H}]_{CG97} + (0.931 \pm 1.037). \tag{b4}
\]

To close, we note, in passing, that the result given in equation (3) is in reasonable agreement with the average \( M_V \) value at \( z = 0.002 \) derived from our HB simulations (§2).

5. A REVISED LMC DISTANCE MODULUS

Equation (4a) implies an \( M_V = 0.644 \pm 0.141 \) mag at \([\text{Fe/H}] = -1.48 \pm 0.07\), which is the mean metallicity derived for LMC RRL variables by Gratton et al. (2004, ZW84 scale). Using a value \( \langle \mathcal{V}_0 \rangle = 19.068 \pm 0.102 \) mag from Gratton et al., one then finds a true distance modulus for the LMC of \( (m-M)_0^{LMC} = 18.42 \pm 0.17 \). If one uses instead the average values for LMC RRL stars independently determined by Borissova et al. (2004), namely \([\text{Fe/H}] = -1.46 \pm 0.09\) dex and \( \langle \mathcal{V}_0 \rangle = 19.45 \pm 0.04 \) mag, with their favored reddening of \( E(B-V) = 0.11 \) mag, one finds \( \langle \mathcal{V}_0 \rangle = 19.11 \pm 0.04 \) mag for a \( M_V = 0.648 \pm 0.142 \) mag; thus \( (m-M)_0^{LMC} = 18.46 \pm 0.15 \). Taking a weighted average over these two results, we arrive at the following distance modulus for the LMC:

\[
(m-M)_0^{LMC} = 18.44 \pm 0.11. \tag{5}
\]

6. CONCLUSIONS

In this Letter, we have established, based on Strömgren photometry, that the star RR Lyr is approximately 0.064 mag brighter than the average for other RRL stars of similar metallicity. We also derive a new reddening value for RR Lyr, namely, \( E(B-V) = 0.015 \pm 0.020 \). These results, along with a newly derived trigonometric parallax for RR Lyr, lead to a revision in the RRL absolute magnitude-metallicity relation, and thus to a revised distance modulus for the LMC.

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