

Letter to the Editor

The distance modulus of the Large Magellanic Cloud based on double-mode RR Lyrae stars

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Abstract. We use double-mode RR Lyrae (RRd) stars from the MACHO variable star database of the Large Magellanic Cloud (LMC) to estimate its distance, by utilizing photometric data, linear pulsation and stellar atmosphere models. If we set $E_{B-V} = 0.11$ and $[M/H] = -1.5$ for LMC, we get $M - m = 18.52$ mag, which is in agreement with the value obtained from Galactic cluster RRd stars. Although the formal statistical error (standard deviation) of $M - m$ derived from the MACHO set is only 0.024 mag, the systematic errors are more substantial. These errors are mostly due to the zero point ambiguity of the temperature scale and to the error of the photometric calibration. However, the fact that the distance moduli obtained in this and in our former studies of cluster RRd and Small Magellanic Cloud beat Cepheids agree so well, implies that the only serious source of error is the zero point of the temperature scale, which should not have larger than ± 0.10 mag effect on the distance modulus.

Key words: stars: fundamental parameters – stars: distances – stars: variables: general – stars: oscillations – stars: horizontal-branch – galaxies: Magellanic Clouds

1. Introduction

The determination of the distance moduli (DM) of the Magellanic Clouds plays an important role in establishing the cosmic distance scale. Mostly due to the analyses of the HIPPARCOS data, there is a renewed effort to pin down this crucial distance within an accuracy of better than ≈ 0.05 mag. However, the question is far from being settled, and the LMC distance moduli obtained with various methods may differ by several tenth of magnitudes, stretching from the ‘short’ ($DM \approx 18.2$, e.g., Stanek et al. 2000) to the ‘long’ ($DM \approx 18.6$, e.g., Feast 1999) distance scales.

In the first paper of this series (Kovács & Walker 1999, hereafter KW99, see also Kovács 2000b) we used RRd stars in Galactic clusters to show that they yield 0.2 – 0.3 mag larger distances than the ones inferred from the Baade-Wesselink absolute magnitudes of RR Lyrae stars. This result leads to $DM \approx 18.5$ mag for the LMC. When the same method is

applied to the Small Magellanic Cloud (SMC) beat Cepheids with 0.51 mag relative distance between the SMC and LMC, we get almost the same DM for the LMC (Kovács 2000a). In the present Letter we directly extend the analysis to the MACHO RRd stars (Alcock et al. 1997, 2000) and show that these give larger distance as well, in fine agreement with the above mentioned independent data sets.

2. Method, data, parameters

We use the same method as in KW99. This implies the utilization of: (a) multicolor data and reddening values on the LMC RRd variables; (b) linear pulsation models; (c) color $\rightarrow T_{\text{eff}}$ transformations given by the static stellar atmosphere models and by the InfraRed Flux Method (IRFM). When considering cluster RRd variables in the context of the LMC distance modulus, we need the same types of information, in addition to the knowledge of the relative cluster distances.

Just briefly mentioning the essence of the method, and referring to KW99 for further details, we note that the pulsation equations yield a relation for the luminosity as a function of the periods, temperature and metal abundance

$$\log L = f(P_0, P_1, \log T_{\text{eff}}, [M/H]). \quad (1)$$

There is also a dependence on other details of the chemical composition, but it has been proved to be rather weak at the relatively low metallicities of the RRd stars in our sample. From the observed dereddened colors we can get estimates on T_{eff} . The metal content $[M/H]$ is preferably obtained from direct spectroscopic observations, but we may also assume that RRd and fundamental mode (RRab) variables have the same $[M/H]$ in a given cluster and apply the method of Jurcsik & Kovács (1996) to determine the metallicity of the RRab stars. Once the luminosity is computed, using the bolometric correction formula of KW99 simply leads to the distance modulus through the comparison with the observed magnitudes.

In the following we give a more detailed description of the parameters entering in the calculation of the LMC distance modulus.

Together with the earlier discoveries of Alcock et al. (1997), the recent analysis of more than 1300 short-period RR Lyrae

stars led to a substantial extension of the known RRd stars in the LMC (Alcock et al. 2000). In the present analysis we include 181 RRd variables, which constitute *all* presently known RRd stars in the LMC. The MACHO instrumental magnitudes have been transformed to the standard Johnson V and Kron-Cousins R_c colors according to the recipe of Alcock et al. (1999). The periods and the average magnitudes are listed in Table 1.¹

For an independent computation of the LMC distance modulus we use globular cluster RRd data compiled by KW99. Relative distance moduli required by this method are checked by the photometric data of Udalski (1998) and Clementini et al. (2000b, hereafter C00b).

The $T_{\text{eff}} = f(\text{color}, \log g, [\text{M}/\text{H}])$ relations are derived from the stellar atmosphere models of Castelli et al. (1997, hereafter C97) with the zero point adjusted to the IRFM results of Blackwell & Lynas-Gray (1994, hereafter BLG94). The required color, $\log g$ and $[\text{M}/\text{H}]$ data are obtained from Clementini et al. (1995). It is important to remark that this approach assumes a uniform shift in $\log T_{\text{eff}}$ between the IRFM and theoretical scales, and that this shift is applicable throughout the relevant parameter regime (i.e., from dwarfs to giants). Additional difficulty might occur because of the inaccuracy of the $[\text{Fe}/\text{H}]$ and $\log g$ values given by the IRFM sources, or the neglect of the $\log g$ dependence in some of those works (e.g., Alonso et al. 1996; 1999, hereafter A96 and A99, respectively). Furthermore, different colors may yield different shifts, producing inconsistency among the derived temperatures at a level of 0.004 in $\log T_{\text{eff}}$. By considering various colors and overlapping samples in the IRFM publications, our current estimates for the zero point differences (in the sense of $\log T_{\text{eff}}$ (source) minus $\log T_{\text{eff}}$ (C97)) are as follows: -0.004 (BLG94), -0.007 (A96); -0.008 (Blackwell & Lynas-Gray 1998); -0.010 (A99). Here we use the scale of BLG94, because it is close to the one used in our previous studies and in the Baade-Wesselink analyses (see KW99). In Sect. 3 we will discuss the effect of the T_{eff} zero point on the distance determination. The final formulae, adjusted to the BLG94 scale are the following

$$\log T_{\text{eff}} = 3.8804 - 0.3213(B - V) + 0.0176 \log g + 0.0066[\text{M}/\text{H}], \quad (2)$$

$$\log T_{\text{eff}} = 3.8928 - 0.4910(V - R_c) + 0.0116 \log g + 0.0012[\text{M}/\text{H}]. \quad (3)$$

As far as the metallicities are concerned, for the three Galactic clusters (M15, M68 and IC4499) we use the data given in KW99. For the LMC field there are very recent direct ΔS measurements by Clementini et al. (2000a). The average $[\text{Fe}/\text{H}]$ value of their 7 RRd variables is -1.6 (or -1.5 if the less accurate low-metallicity star is left out). Here we accept $[\text{Fe}/\text{H}] = -1.5$ for the LMC RRd variables. In principle, one should use variable dependent metallicity as it follows from the analysis of the period ratio diagram (Popielski et al. 2000). However, tests have shown that in the present context and data quality, this dependence has a rather negligible effect on the final conclusion.

¹ Table 1 is available only in electronic form at CDS (ftp 130.79.128.5)

Table 2. Relative distance moduli (LMC minus IC4499) and reddenings of LMC field RR Lyrae stars

Source	N	ΔDM	E_{B-V}
Field (OGLE RRab):	100	2.04	0.13
RRd(MACHO):	181	1.99	0.11
RRd(C00b):	10	2.03	0.09

Therefore, we use the same metal abundance for all variables in the LMC.

In order to compare the direct DM obtained from the LMC field RRd variables with the ones computed from cluster RRd stars, we have to know the relative distances and reddenings. In calculating these quantities we follow essentially the method of Kovács & Jurcsik (1997) which employs the periods and the Fourier decompositions of the light curves in computing the physical parameters of RRab stars. In the present implementation of the method we use only the period in deriving the relations for the reddening-free quantities (e.g., $W = V - 3.1(B - V)$, $(B - V)_0$). This approximation is necessary, because of the limited information available on the LMC OGLE data set. Nevertheless, the results are sufficiently accurate for the present purpose (see also Kovács & Walker 2000).

It is also possible to make a direct comparison between the colors and distance moduli of the RRd variables in LMC and IC4499. Since they both have very similar metallicities and periods, we may assume that their average intrinsic colors and luminosities are also very similar. The average quantities for the 181 MACHO LMC RRd stars are the following: $\langle V \rangle = 19.30$, $\langle V - R \rangle = 0.246$, $\langle P_0 \rangle = 0.49$. Similarly, from C00b for the 10 RRd stars we get: $\langle V \rangle = 19.29$, $\langle B - V \rangle = 0.37$, $\langle P_0 \rangle = 0.48$. The same quantities for the 15 RRd stars in IC4499 are the following: $\langle V \rangle = 17.66$, $\langle B - V \rangle = 0.50$, $\langle V - R \rangle = 0.31$, $\langle P_0 \rangle = 0.48$. Simple subtraction of the corresponding quantities leads to the results summarized in Table 2.

The close match between the relative distance moduli and reddenings calculated from the different data sets is very encouraging as far as the consistency among the photometric zero points are concerned. We note in passing that relative distance moduli calculated by the method of Kovács & Jurcsik (1997) from the RRab variables of four LMC globular clusters also yield 2.04 mag for the average of the relative distances between those LMC clusters and IC4499.

3. Results

In the following we derive the distance of the LMC from two independent data sets containing RRd stars: (1) Galactic globular clusters; (2) MACHO LMC field variables. We use composition (d) of KW99 ($X = 0.76$, with solar-type distribution of heavy elements), and OPAL'96 opacities (Iglesias & Rogers 1996).

Relative distance moduli between the three Galactic globular clusters and their reddenings are from KW99. These parameters have been calculated by the method of Kovács & Jurcsik (1997). We fix the relative distance modulus between LMC and

Table 3. Derived distance moduli for the LMC. Columns 5–8 show the changes in the distance modulus, if E_{B-V} , $[M/H]$, $\log T_0$, P_1/P_0 (observed) are changed by +0.03, +0.2, +0.005 and +0.001, respectively. Column 9 shows the effect of changing X from 0.76 to 0.70

Cluster	$[M/H]$	E_{B-V}	DM_{LMC}	$\Delta DM_{E_{B-V}}$	$\Delta DM_{[M/H]}$	$\Delta DM_{\log T_0}$	$\Delta DM_{P_1/P_0}$	$\Delta DM_{Comp.}$
M15	-2.3	0.07	18.52	0.04	0.05	0.07	0.05	0.01
M68	-2.0	0.03	18.47	0.05	0.08	0.07	0.06	0.02
IC4499	-1.5	0.22	18.50	0.06	0.15	0.08	0.05	0.04
LMC	-1.5	0.11	18.52	0.04	0.14	0.08	0.06	0.04

IC4499 at 2.03 mag and the LMC reddening at $E_{B-V} = 0.11$. Column 4 of Table 3 shows the derived distance moduli. The agreement is very good between the different estimates. This shows that the relative values of all parameters have been chosen properly. Our more serious concern is the effect of the various zero point shifts. In the subsequent columns of Table 3 we show the changes of DM due to these shifts and also to those ambiguities which occur in the pulsation models. Except for the case of changing $[M/H]$, negative shifts in the parameters cause the same amount of negative offsets in DM . If $[M/H]$ is decreased, the corresponding changes are up to 0.04 mag smaller in DM than if $[M/H]$ is increased by the same amount. The adopted values for the changes of the tested quantities are merely to demonstrate their effects without implying that these changes can, in fact, be expected. In particular, it is rather unlikely that for Galactic globular clusters the reddenings were off by 0.03 mag or more. In any case, zero point effects in E_{B-V} are not serious in our method, because they are compensated in the derived DM through the nearly parallel effects in the calculated luminosity and in the magnitude corrections for reddening (see also KW99).

We see that almost all zero point errors cause uniform shifts in the distance moduli, which are independent of the stellar population. The only exception is the zero point of the metallicity scale. Variables with higher $[M/H]$ are more affected by this zero point ambiguity. Therefore, metallicity change in itself cannot decrease the distance modulus too much, because this would result in a substantial increase of the differences between the computed distance moduli.

Ambiguity in the zero point T_0 of the color $\rightarrow T_{\text{eff}}$ transformation is the main source of error in the present method. However, we note that even if we accepted the temperature scale of A99, which is the lowest among the available IRFM scales, the derived distances would be still around ≈ 18.4 mag. We are not aware of any studies strongly indicating the possibility of more dramatic lowering of the temperature scale. We note that the method of color averaging might have also some effect on the derived effective temperature. Here we use magnitude averaging, which has a tendency of yielding redder equilibrium colors, i.e., lower temperatures than the static ones (Bono et al. 1995).

Effect of period ratio change due to nonlinearity is rather small. Past and very recent works on convective RRd models show that period ratio changes are within 0.002. In the case of RRd models, there is a trend of the nonlinear convective period ratios being smaller than the linear radiative ones (Kolláth &

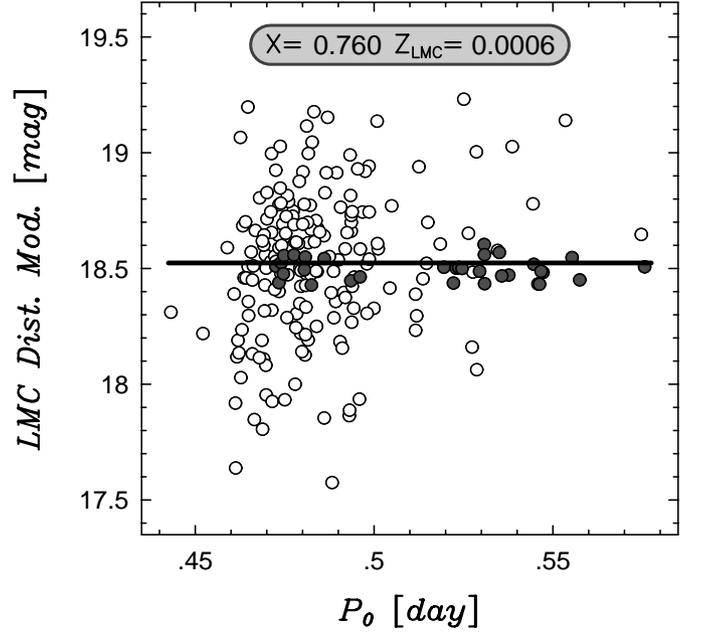


Fig. 1. Individual distance moduli from the LMC (open circles) and from Galactic RRd stars (gray circles). The horizontal line shows the average distance modulus derived from the LMC variables

Buchler 2000). This would result in a slight *increase* in the derived DM , because our results are based on radiative linear models, but on the other hand, nonlinear period increase might compensate for this effect.

In the last column we show the small change due to varying hydrogen content from $X = 0.76$ to 0.70 (mixtures (c) and (d) in KW99). Finally, to exhibit the distribution of the distance moduli derived for the individual stars, Fig. 1 shows these values as a function of the period. The huge scatter of the LMC stars is partially counterbalanced by their large number, which brings the statistical error down to 0.024 mag for the distance modulus derived from these variables. This can be compared with the value of 0.015 mag, valid for the Galactic RRd stars. The largest contribution to the $\sigma(DM) = 0.32$ mag scatter of the LMC stars comes from the photometric errors. By using the error estimates of $\sigma_V = 0.02$, $\sigma_{(V-R)} = 0.03$ (see Alcock et al. 1999) we get 0.21 mag for the standard deviation of the individual distance moduli. We note that the result is most sensitive to $\sigma_{(V-R)}$. For example, with $\sigma_{(V-R)} = 0.04$ we get $\sigma(DM) = 0.26$ mag. The rest of the scatter comes from the metallicity dispersion,

inhomogeneous reddening and possibly from the spatial extent of the LMC.

4. Conclusions

The recent revision of the MACHO RRd magnitudes (Alcock et al. 1999) enabled us to calculate the distance of the LMC directly from the observed magnitudes, colors and periods. This shows a very good agreement with the independent estimate based on Galactic globular cluster RRd stars and SMC beat Cepheids (Kovács 2000a). They all give $M - m \approx 18.5$ mag, which lends further support to the ‘long’ distance scale. The largest source of systematic error is the potential ambiguity in the zero point of the temperature scale. Even this is not likely to cause the large effect, which would be necessary to lower the distance modulus by ≈ 0.3 mag, the value required by some current estimates based on other methods (e.g., Stanek et al. 2000). This amount of change would demand about 300K lower temperature scale than the one used in this work. Since our adopted scale is only 100 K hotter than the presently published lowest infrared flux scale of Alonso et al. (1999), we think that it is highly unlikely that the required lowering of the distance modulus is possible by temperature change alone. Consequently, we would need some ‘conspiracy’ with metallicity, reddening or other parameters, so as to get the necessary decrease in the distance modulus. This situation is also not very probable, because, although the strongest effect comes from the metallicity, this is primarily differential i.e., the distance moduli derived from the low metallicity clusters would not be seriously affected. This would lead to inconsistency among the distance moduli, because the relative distances, being empirically determined, are independent from the adopted metallicities. It is also worthwhile to mention that the metallicity values used in this and in our previous studies are in very good agreement with the ones published by independent spectroscopic studies and that these metallicities minimize the differences between the LMC distance moduli derived from various double-mode stars.

We conclude that the application of standard temperature and metallicity scales leads to the ‘long’ RR Lyrae distance scale, which, except for a drastic lowering of the temperature scale, is not possible to match with the ‘short’ distance scale.

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