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THE DISTANCE TO THE LARGE MAGELLANIC CLOUD CLUSTER RETICULUM FROM THE *K*-BAND PERIOD-LUMINOSITY-METALLICITY RELATION OF RR LYRAE STARS[1]

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ABSTRACT

We present new and accurate near-infrared *J*- and K_s-band data of the Large Magellanic Cloud cluster Reticulum. Data were collected with SOFI at the New Technology Telescope and covered an area of approximately $5' \times 5'$ around the center of the cluster. Current data allowed us to derive accurate mean *K*-band magnitudes for 21 fundamental (RR*ab*) and 9 first-overtone (RR*c*) RR Lyrae stars. On the basis of the semiempirical *K*-band period-luminosity-metallicity (PLZ_K) relation we have recently derived, we find that the absolute distance to this cluster is 18.52 ± 0.005 (random) ± 0.117 (systematic). Note that the current error budget is dominated by systematic uncertainty affecting the absolute zero-point calibration and the metallicity scale.

Subject headings: stars: evolution — stars: oscillations — stars: variables: other

1. INTRODUCTION

Absolute distances of RR Lyrae stars play a fundamental role in stellar astrophysics, and the reasons are manifold. They are widely adopted to establish the absolute age of globular clusters (GCs) and to properly compare predicted and empirical color-magnitude diagrams. Moreover, they are robust stellar tracers of low-mass, old populations and are ubiquitous across the Galactic spheroid as well as in Local Group galaxies. During the last few years a paramount theoretical and observational effort has been devoted to the RR Lyrae distance scale not only to improve the intrinsic accuracy but also to constrain the occurrence of deceptive systematic errors (Caputo et al. 2000; Walker 2000; Bono 2003; Cacciari & Clementini 2003; Alves 2003).

In a series of previous papers (Bono et al. 2001, 2002, 2003, hereafter B01, B02, B03) we have drawn attention to the *K*-band period-luminosity-metallicity (PLZ_K) relation of RR Lyrae stars. This relation was originally discovered by Longmore et al. (1990, hereafter L90) and presents several indisputable advantages when compared with other methods available in the literature. In particular, the PLZ_K relation is only marginally affected by evolutionary effects, as well as by a spread in stellar mass inside the instability strip. Moreover, it is only weakly affected by uncertainties in the reddening correction and shows a linear trend when moving from metal-poor to metal-rich objects. Current theoretical predictions appear to be in very good agreement with empirical observations, and indeed the pulsation parallax to RR Lyr itself estimated by B02 is in very good agreement with the trigonometric parallax measured by Benedict et al. (2002) with the Fine Guidance Sensor on board the *Hubble Space Telescope* (*HST*).

Although the theoretical framework concerning the PLZ_K relation has been thoroughly discussed, only a few investigations have been devoted to near-infrared (NIR) observations of cluster and field RR Lyrae stars. In fact, with the exception of the *K*-band data collected by L90 for cluster RR Lyrae and Baade-Wesselink RR Lyrae stars (see B03 for a detailed list), only one investigation has been devoted to RR Lyrae stars in the Galactic bulge (Carney et al. 1995). The observational scenario has been recently complemented with new *K*-band data collected by Butler (2003), using the adaptive optics camera on the 3.5 m Calar Alto telescope, for a small sample of RR Lyrae stars located in the very center of the GC M3. The above discussion shows quite clearly that we lack new and accurate NIR data not only to supply a sound empirical estimate of both the slope and the zero point of the PLZ_K relation but also to improve current empirical constraints on the metallicity dependence. To fill this gap we undertook an observational project aimed at providing a comprehensive observational investigation of cluster and field RR Lyrae stars in the NIR *J* and K_s bands.

In this investigation we present *K*-band data for RR Lyrae stars in the LMC cluster Reticulum. We selected this cluster for the following reasons: it presents a sizable sample of well-studied RR Lyrae stars (32; Walker 1992), its central density is very low ($\log \rho_0 \approx 0\ M_\odot\ \mathrm{pc}^{-3}$; Peterson & Kunkel 1977) and therefore the NIR photometry is not seriously affected by crowding, and the metal content of this cluster has been estimated using medium-resolution spectra ($[\mathrm{Fe/H}] \approx = -1.71 \pm 0.1$; Suntzeff et al. 1992). In § 2, we present the observations and the fit to the K_s-band light curves, while in § 3 we discuss the new distance determination together with intrinsic and systematic uncertainties affecting the current estimate.

2. OBSERVATIONS

Near-infrared *J* and K_s images of Reticulum were collected in three different runs from 1999 December to 2002 February

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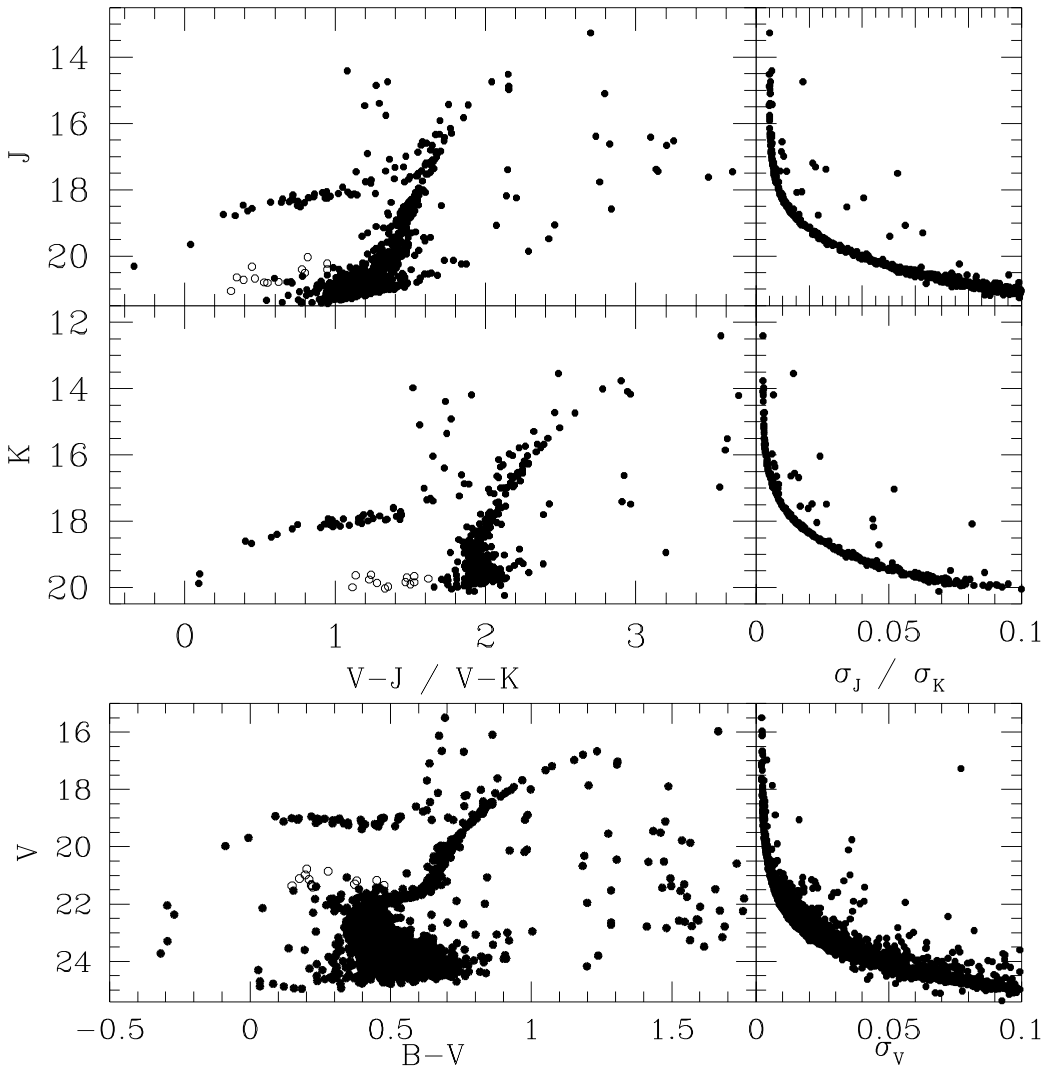

FIG. 1.—Reticulum CMDs in the J, $V-J$ (*top*), K, $V-K$ (*middle*), and V, $B-V$ (*bottom*) bands. The boxes on the right show the intrinsic photometric errors given by ALLFRAME. The NIR photometry is quite accurate, and indeed, for $J \approx 18.5$ and $K \approx 18$, i.e., the typical magnitudes of RR Lyrae stars, the intrinsic accuracy is systematically better than 0.02. The open circles mark the position of blue stragglers detected in the K, $V-K$ CMD and then cross-identified in the other CMDs. By adopting the following selection criteria, |sharpness| ≤ 1.1 and $\chi \leq 0.5$, we detected approximately 850 and 550 stars in the J and in the K_s bands, respectively.

with SOFI at the New Technology Telescope of ESO La Silla. The seeing conditions during these observing runs were good and range from 0″.5 to 1″.3. We collected 46 J and 171 K_s-band frames ($5' \times 5'$, pixel size = 0″.292) centered on the cluster, and the individual exposure times range for the J band from 10 to 30 s and for the K_s band from 10 to 120 s. We detected 30 of the 32 RR Lyrae stars present in this cluster, and the number of phase points for each object is approximately 12. Raw frames were prereduced using standard IRAF procedures. To improve the photometric accuracy along the light curves, we performed several tests using different techniques to stack the images and different criteria to select point-spread function (PSF) stars across the individual frames, as well as using different strategies to perform the photometry over the entire data set. We found that the best intrinsic accuracy can be achieved if we do not stack the images. We selected a reasonable number of PSF stars ($\approx$25) for each frame and adopted a variable PSF. Moreover, the NIR (J, K_s) frames have been simultaneously reduced with DAOPHOT/ALLFRAME together with a few V-band images to improve the accuracy of individual measurements and limiting magnitudes. Optical (*UBVI*) data have been collected during the same observing runs with SUSI2 at the same telescope. A detailed description of observing and data reduction strategies will be discussed in a companion paper. The absolute photometric calibration of J and K_s ESO magnitudes into the Las Campanas Observatory system was performed using the standard star 9109 (HST S055-D) measured by Persson et al. (1998). We did not apply any correction to transform the K_s into the K band because of the marginal difference (Lidman et al. 2002). This star was measured 10 times at air masses that bracket the observations of Reticulum, and the accuracy of the calibration is of the order of 0.002 mag in the K band.

Figure 1 shows the color-magnitude diagrams (CMDs) in the J, $V-J$ (*top*), K, $V-K$ (*middle*), and V, $B-V$ (*bottom*) bands together with the intrinsic photometric accuracy of the mean magnitudes provided by ALLFRAME. Data plotted in this diagram show quite clearly that the intrinsic accuracy for typical RR Lyrae luminosities reaches 0.01 at $J \approx 18.5$ and 0.015 at $K \approx 18$. We detected approximately 850 and 550 stars in the J and K bands, while the limiting magnitudes are $\approx$20.5 and $\approx$20, respectively. Note that the sample of hot stars

TABLE 1
Weighted Intensity-averaged K Magnitudes

ID	log P (days)	Epoch (HJD)	$\langle K \rangle$ (mag)	σ_K (mag)	Type
4	−0.45195	2448206.006	18.058	0.017	*c*
7	−0.20853	2448206.070	17.824	0.015	*ab*
25	−0.29657	2448206.125	18.020	0.018	*ab*
35	−0.27164	2448206.285	17.963	0.015	*ab*
36	−0.48161	2448206.220	18.170	0.018	*c*
37	−0.29401	2448206.010	18.003	0.016	*ab*
38	−0.29043	2448206.968	18.001	0.020	*ab*
41	−0.45157	2448206.150	18.055	0.017	*d*
49	−0.28158	2448206.708	17.958	0.017	*ab*
57	−0.28938	2448206.055	17.933	0.017	*ab*
64	−0.28918	2448206.250	17.983	0.018	*ab*
67	−0.18245	2448206.515	17.746	0.014	*ab*
72	−0.45073	2448206.070	18.060	0.018	*d*
77	−0.45276	2448206.258	18.061	0.019	*c*
80	−0.24272	2448206.295	17.888	0.015	*ab*
97	−0.22529	2448206.245	17.827	0.016	*ab*
98	−0.44894	2448206.000	18.077	0.018	*d*
99	−0.21497	2448206.535	17.785	0.014	*ab*
100	−0.23162	2448206.360	17.835	0.016	*ab*
108	−0.32917	2448206.100	18.062	0.016	*ab*
110	−0.45906	2448206.100	18.031	0.017	*d*
112	−0.25124	2448206.250	17.863	0.019	*ab*
117	−0.29205	2448206.245	17.930	0.017	*ab*
135	−0.19047	2448206.510	17.783	0.014	*ab*
137	−0.26363	2448206.455	17.954	0.016	*ab*
142	−0.24504	2448206.200	17.910	0.018	*ab*
145	−0.21988	2448206.338	17.786	0.018	*ab*
146	−0.31439	2448206.044	18.035	0.019	*ab*
151	−0.49493	2448206.134	18.108	0.019	*c*
181	−0.52832	2448206.122	18.209	0.018	*c*

Note.—Based on the template fitting method of Jones et al. (1996) and the K-band photometry presented in this work. The epochs are Heliocentric Julian Date. Types *ab* and *c* are for fundamental and first-overtone RR Lyrae stars, respectively, while type *d* is for candidate mixed-mode variables.

located at $K \approx 19.75$ and $1.0 \leq V-K \leq 1.6$ are blue straggler stars, as supported by the cross-identification with the optical CMD (*open circles*). This suggests that current photometry almost approaches the turnoff region.

To further improve the intrinsic accuracy of the RR Lyrae mean magnitudes, we decided to perform a fit of the individual phase points measured by ALLFRAME with a template curve. This approach allows us a better propagation of individual errors for the final mean magnitude and avoids the spurious fluctuations introduced by the binning of phase points. Jones et al. (1996) have developed a template-fitting technique for determining mean magnitudes in the K band for RR Lyrae stars from few phase observations. They have determined five different template shapes depending on the type of variability (RR*ab* or RR*c*) and on the B amplitude of the variable and described each of these templates with a Fourier series. We have adopted their method, and for each star we computed the corresponding Fourier template on the basis of the ephemerides and the B amplitudes from V. Ripepi et al. (2004, in preparation). The candidate RR*d* stars have been treated as RR*c* variables because of their small amplitudes and relatively short periods.

For each observed phase point we can compute the best estimate of the mean magnitude over the phase of the variable by subtracting the template magnitude from the observed magnitude, $\langle K(\phi)\rangle = K_{\rm obs}(\phi) - K_{\rm template}(\phi)$. We computed the weighted intensity-averaged magnitude over all the observed phase points for each variable star. The resulting mean magnitudes and their associated intrinsic errors are listed in Table 1. Figure 2 shows the mean $\langle K \rangle$ magnitude as a function of $\log P$. Note that the periods of first-overtone (FO) variables (*open circles*) in Figure 2 have been fundamentalized, i.e., $\log P_F = 0.127 + \log P_{\rm FO}$. It can be seen that there is an excellent correlation. Linear regression gives

$$\langle K \rangle = -2.16(\pm 0.09) \log P + 17.352(\pm 0.025), \qquad (1)$$

with a standard deviation of only 0.03 mag. This is a remarkable result for a standard candle.

3. DISCUSSION AND FINAL REMARKS

On the basis of the mean K magnitudes from the previous section we now proceed to determine the distance to the Reticulum cluster. To further improve the theoretical calibration of the PLZ_K relation, B03 devised a new pulsation approach that relies on mean K-band magnitudes and $V-K$ colors. In particular, they derived new PLZ_K relations (see their relations [3] and [4]) and period-luminosity-color-metallicity ($PLCZ_{(V,K)}$) relations (see their relations [7] and [8]) that

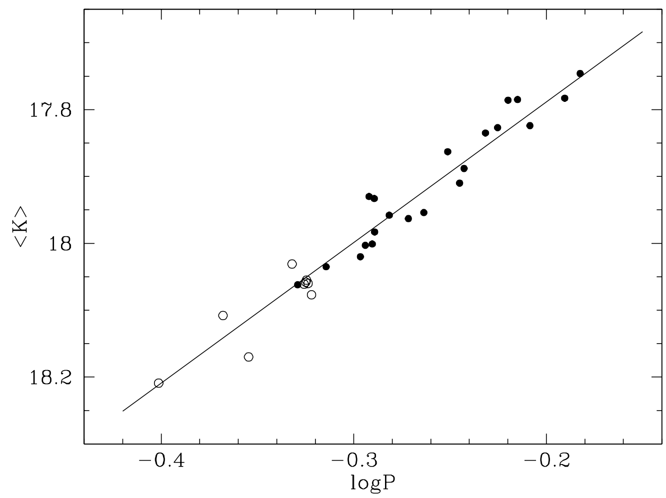

FIG. 2.—The $\log P$-$\langle K\rangle$ relation for the Reticulum RR Lyrae stars. Open symbols show the RR*c* stars after their periods have been fundamentalized by adding 0.127 to $\log P$. Filled symbols are RR*ab* stars, and the straight line represents the theoretical prediction from B03 for the derived distance modulus.

include the luminosity term. Note that these relations when compared with theoretical predictions by B01 present three main advantages: (1) they rely on a larger set of pulsation models, (2) independent theoretical relations have been derived for fundamental and first-overtone pulsators, and (3) the new PLZ_K and $PLCZ_{(V,K)}$ relations were derived by adopting predicted mass values for each assumed chemical composition, while B01 adopted an ensemble average. To base the calibration of the zero point, as well as that of the coefficient of the metallicity term of the new PLZ_K relation, on empirical data, B03 adopted a sample of field RR Lyrae stars for which good *V*- and *K*-band light curves, accurate reddening corrections, and metal abundances were available in the literature. For fundamental mode pulsators they found

$$M_K = -0.770(\pm 0.044) - 2.101 \log P + 0.231(\pm 0.012)[\mathrm{Fe/H}]. \quad (2)$$

Suntzeff et al. (1992) have determined the metallicity of the Reticulum cluster to be $[\mathrm{Fe/H}] = -1.71 \pm 0.1$ on the basis of spectroscopy of the Ca II triplet at around 860 nm for nine individual stars in the cluster. Entering this value in equation (2), we can determine the distance modulus, $(m-M)_K = \langle K\rangle - M_K$, to each star. Forming the weighted average of these estimates, we find for the RR*ab* stars a value of $(m-M)_K = 18.531 \pm 0.006$, while for the RR*c* stars, using the fundamentalized periods, we find $(m-M)_K = 18.539 \pm 0.009$, and for the complete sample, we find $(m-M)_K = 18.534 \pm 0.005$.

The reddening toward Reticulum has been determined by Walker (1992), who finds a very low value of $E(B-V) = 0.03 \pm 0.02$. We combine this value with the reddening law from Cardelli et al. (1989) of $A_K = 0.114 \times 3.1 \times E(B-V)$, which gives a minuscule absorption in the *K* band of $A_K = 0.011$ mag. Correcting the modulus for the reddening, we find a best estimate of $(m-M)_0 = \mu_0 = 18.523 \pm 0.005$, where the error estimate only considers intrinsic random errors. We also performed a detailed check of the systematic uncertainties affecting distance estimates based on the semiempirical relation derived by B03. We selected the Galactic globular clusters (GGCs) for which both optical and NIR mean magnitudes are available. To avoid subtle uncertainties in the reddening corrections, we only selected GGCs with reddening corrections smaller than 0.2. We ended up with four GGCs whose metallicities range from $[\mathrm{Fe/H}] = -1.27$ (M5) to -2.26 (M15). To estimate the difference in the distance moduli, we adopted distances based on the Baade-Wesselink (BW) calibration provided by Fernley (1994), as well as ones based on the first-overtone blue edge (FOBE) provided by Caputo et al. (2000). Data listed in the last two columns of Table 2 show that the difference ranges from $\Delta\mu = 0.32$ for the more metal-poor cluster (M15) to $\Delta\mu = 0.10$ for the more metal-rich cluster (M5).

This finding further strengthens the result obtained by B03, i.e., that the difference between distances based on PLZ_K and on the BW method depend on the mean metallicity and it decreases in the metal-rich regime (see Figs. 6 and 8 in B03). Unfortunately, we still lack accurate mean *K*-band magnitudes for RR Lyrae stars in a larger sample of metal-rich GGCs. Moreover, current uncertainties affecting distance moduli based on mean *V*-band magnitudes are systematically larger than 0.1 mag. This hampers any precise quantitative conclusion on the systematic uncertainty affecting the PLZ_K distance scale.

It is noteworthy that cluster distances presented here appear to be systematically larger than distances based on the FOBE method and on the PLZ_K calibration based on theoretical models provided by B01. The semiempirical calibration by B03 presents a steeper dependence on the metallicity (0.231 vs. 0.167), and the reasons for the difference between the

TABLE 2

COMPARISON OF DISTANCE MODULI BASED ON RR LYRAE STARS FOR DIFFERENT GGCS

ID	[Fe/H][a]	$E(B-V)$[b]	$\langle V\rangle$[c]	σ_V	μ_0^V (BW)[d]	μ_0^V (FOBE)[e]	μ_0^K[f]	$\Delta\mu$[g]	$\Delta\mu$[h]
NGC 5139 (ω Cen).......	−1.62	0.12	14.57	0.12	13.57 ± 0.16	...	13.77 ± 0.04	0.20	...
NGC 5272 (M3)...........	−1.57	0.01	15.61	0.12	14.94 ± 0.16	14.97 ± 0.07	15.15 ± 0.06	0.21	0.18
NGC 5904 (M5)...........	−1.27	0.03	15.06	0.08	14.26 ± 0.13	14.28 ± 0.07	14.37 ± 0.09	0.11	0.09
NGC 7078 (M15).........	−2.26	0.10	15.82	0.08	15.01 ± 0.13	15.17 ± 0.07	15.32 ± 0.10	0.30	0.15

[a] Mean cluster metallicity according to Harris (1996).
[b] Cluster reddening according to Harris (1996).
[c] Mean visual magnitude according to: ω Cen, Olech et al. (2003); M3, Corwin & Carney (2001); M5, Caputo et al. (1999); M15, Silbermann & Smith (1995).
[d] True distance moduli based on the Baade-Wesselink calibration provided by Fernley (1994).
[e] True distance moduli based on the first-overtone blue edge method suggested by Caputo et al. (2000).
[f] True distance moduli based on *K*-band mean magnitudes for RR Lyrae stars collected by L90 and the semiempirical relation derived by B03.
[g] Difference in distance moduli between the PLZ_K relation and the BW method.
[h] Difference in distance moduli between the PLZ_K relation and the FOBE method.

empirical and theoretical scales are not clear yet (see also Carney et al. 1992). Finally, we note that the current distance estimate to ω Cen is also 0.1 mag larger than the distance modulus derived by Thompson et al. (2001) on the basis of the eclipsing binary OGLEGC 17. Although the analysis of current uncertainties affecting the RR Lyrae distance is far from being definitive, we decided to adopt a systematic uncertainty of 0.1 in the calibration of the zero point.

The uncertainty on the reddening correction is quite negligible, but we have to account for the uncertainty in the metallicity and in the metallicity scale. Equation (2) was derived using the metallicity estimates provided by Fernley et al. (1998) and Zinn (1985) for field and cluster RR Lyrae stars. The metallicities of field RR Lyrae stars rely on a calibration of the ΔS method provided by Fernley & Barnes (1997), i.e., $[\mathrm{Fe/H}] = -0.13 - 0.195\Delta S$, that is quite similar to the calibration provided by Clementini et al. (1995), $[\mathrm{Fe/H}] = -0.08 - 0.195\Delta S$. These calibrations supply metal abundances quite similar to the Zinn & West (1984) metallicity scale. On the other hand, Gratton (1999) provided a new calibration, $[\mathrm{Fe/H}] = -0.03 - 0.176\Delta S$, that relies on the Carretta & Gratton (1997) metallicity scale. By accounting for these empirical uncertainties of the zero point and the slope, as well as the systematic uncertainties affecting the metallicity scale (Rutledge et al. 1997; Kraft & Ivans 2003), we estimate the uncertainty of the metallicity to be of the order of 0.25 dex. This means that the uncertainty of the mean metallicity in equation (2), as well as in the cluster metallicity, introduces an uncertainty of the order of 0.06 mag in the current distance determination. Therefore, we end up with a distance to Reticulum of 18.52 ± 0.005 (random) ± 0.117 (systematic).

Reticulum is located 11° away from the center of the LMC, and therefore we can only supply weak constraints on the absolute distance to the LMC itself. According to our optical photometry and by assuming a mean reddening of $E(B-V) = 0.03 \pm 0.02$ (Walker 1992), the mean visual magnitude of RR Lyrae stars in Reticulum is $V_0 = 18.96 \pm 0.05$ mag. Note that this estimate is in very good agreement with the estimate provided by Walker (1992), i.e., $V_0 = 18.98 \pm 0.04$. Recent estimates of the mean visual magnitude of RR Lyrae stars in the LMC bar range from $V_0 = 19.05 \pm 0.06$ (108 stars) by Clementini et al. (2003) to $V_0 = 18.90 \pm 0.02$ (7110 stars) derived by the OGLE team (Soszynski et al. 2003) and to $V_0 = 18.99 \pm 0.02$ (random) ± 0.16 (systematic) (80 first overtones) derived by the MACHO team (Alcock et al. 2004). The key differences in these estimates are statistics, absolute zero-point calibration, and reddening correction. It goes without saying that according to these estimates, the position of Reticulum ranges from $\approx$3 kpc in front of the LMC to $\approx$2 kpc beyond the LMC. New and homogeneous NIR data for a sizable sample of RR Lyrae stars in the LMC bar are mandatory to settle the uncertainty on the relative position of this cluster.

The empirical evidence brought out by current data suggests that the PLZ_K relation is characterized by a global accuracy better than 0.12 mag. Note that the current discrepancy between horizontal branch evolutionary models constructed with different assumptions concerning the input physics is of the order of 0.1–0.15 mag (Cassisi et al. 1999; VandenBerg et al. 2000). However, the most recent systematic survey of K-band data for cluster RR Lyrae stars dates back to L90. Therefore, new and homogeneous NIR data for GGCs with sizable samples of RR Lyrae stars are strongly required to shed new light on this long-standing problem. At the same time, a new empirical calibration of the PLZ_K relation based on RR Lyrae stars for which heavy-element abundances have been measured on high-resolution spectra is also necessary.

The intrinsic accuracy of the PLZ_K relation also seems very promising in providing a new distance scale for GCs that can allow us to improve their absolute age estimate. It is noteworthy that new cluster data will allow us to derive an independent PLZ_K relation for first-overtone RR Lyrae stars and in turn to further improve the intrinsic accuracy of this method. Finally, because of the marginal dependency on reddening corrections, this relation could also be confidently adopted to derive the three-dimensional structure not only of the Magellanic Clouds but also of the Galactic bulge.

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