A “PULSATIONAL” DISTANCE DETERMINATION FOR THE LARGE MAGELLANIC CLOUD

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ABSTRACT

We present results from the theoretical modeling of the observed B,V light curves of 14 RR Lyrae stars in the Large Magellanic Cloud. The sample includes seven fundamental and seven first-overtone pulsators covering the metallicity range from $-2.12$ to $-0.79$ dex in [Fe/H], with an average value of $-1.54$ dex. Masses, intrinsic luminosities, effective temperatures, and reddening were derived by fitting high-accuracy multiband light curves available for these RR Lyrae stars to nonlinear convective pulsation models. Individual distance moduli were determined for each variable and lead to an average distance modulus for the Large Magellanic Cloud of $\mu_0 = 18.54 \pm 0.02$ ($\sigma = 0.09$ mag, standard deviation of the average), in good agreement with the “long” astronomical distance scale.

Key words: galaxies: distances and redshifts — Magellanic Clouds — stars: evolution — stars: horizontal-branch — stars: variables: other

1. INTRODUCTION

One of the most debated issues of modern astrophysics is the definition of the local distance scale and the distance of its first step, the Large Magellanic Cloud (LMC), in particular. Indeed, current calibrations of the extragalactic distance scale and consequent evaluations of the Hubble constant rely on the classical Cepheid period-luminosity relations with the zero point fixed by some assumption of the LMC distance (see, e.g., Freedman et al. 2001; Tammann et al. 2003). Recent determinations of the LMC distance modulus, based on Population I or II distance indicators, cover the range 18.3–18.7 mag (see discussions in Cacciari 1999; Walker 1999; Carretta et al. 2000; Caputo et al. 2000). However, in the last couple of years different distance indicators have followed the trend to converge to a common value of $\mu_{\text{LMC}} = 18.52 \pm 0.02$ mag, on the basis of updated accurate photometric data for both RR Lyrae and red clump stars, as well as revised techniques and consistent reddening evaluations (see discussions in Clementini et al. 2003, hereafter C03; Walker 2003; and Alves 2004).

Among the different methods exploiting the radially pulsating stars as standard candles, a quite innovative and promising technique is represented by the fitting of the observed light and radial velocity curves of a pulsating star to those predicted by nonlinear pulsation models (see, e.g., Wood et al. 1997, hereafter WAS97; Keller & Wood 2002; Bono et al. 2000, 2002, hereafter BCM00 and BCM02, respectively; Di Fabrizio et al. 2002). This technique is based on the direct comparison between observed and predicted curves, rather than involving related parameters such as pulsation amplitudes and Fourier parameters, and performs the theoretical reproduction of both general features (period, shape, and amplitude) and morphological details, such as bumps and humps, of the observed curves. Given the sensitivity of the detailed morphology of the curve to the model input parameters, as well as to the physical and numerical assumptions, the fitting of actual light and radial velocity curves offers a unique opportunity to obtain sound estimates of the intrinsic stellar properties of the variables, providing at the same time a key test of the theoretical predictions.

High-accuracy observational data, consisting of well-sampled multiband light curves and knowledge of the related pulsation characteristics (namely, period, colors, and amplitudes) and of the metallicity of the variable stars are needed for a meaningful application of the method. The output of the procedure is a set of models for fixed period and metal abundance and with varying mass, luminosity, and effective temperature, among which the best-fitting model is that best reproducing the observed characteristics of the pulsation, within acceptable values of the derived intrinsic parameters.

In the case of variables of RR Lyrae type this technique has already provided very good results for Galactic field first-overtone RR Lyrae stars (see BCM00; Di Fabrizio et al. 2002), whereas for the fundamental-mode pulsators satisfactory results were obtained except for the long-period variables close to the red edge of the RR Lyrae instability strip (see Castellani et al. 2002).

As for the classical Cepheids, a similar technique was early applied by WAS97 to the LMC bump Cepheid HV 905. More recently, relying on the same theoretical pulsational scenario as in BCM00, the method was applied to two LMC fundamental-mode Cepheids showing well-defined bumps along the decreasing (short-period) and the rising (long-period) branches of the light curve (BCM02), based on data from the OGLE catalog. A good fit was obtained for both variables and for an LMC distance modulus ranging from 18.48 to 18.58 mag (see BCM02 for details), in agreement with results by C03. An independent application to the MACHO V and R light curves of

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1 Based on observations collected at the European Southern Observatory, proposals 62.N-0802, 66.A-0485, and 68.D-0466.

2 We note that mass, luminosity, and effective temperature are not independent variables because of the existence of a period-density relation for pulsating stars.

3 Available at http://sirius.astrouw.edu.pol/~ogle/ogle2/dia.
20 bump Cepheids in the LMC (including HV 905) was performed by Keller & Wood (2002) on the basis of the WAS97 nonlinear pulsation code. They obtained a mean LMC distance modulus of 18.55 ± 0.02 (intrinsic error of the average).

In the cases of both RR Lyrae stars and classical Cepheids, the best-fit models based on the BCM00 theoretical scenario seem to suggest that the standard value of the mixing-length parameter ($l/H_p = 1.5$) adopted to close the dynamical convective equation system is suitable to reproduce the light variations of variables in the blue region of the instability strip. A higher value of $l/H_p$ is needed instead toward the red region of the fundamental-mode instability strip (see, e.g., BCM02). This occurrence is confirmed by results based on other independent “pulsational” methods to constrain the RR Lyrae and globular cluster distance scale, in particular, the period-amplitude relations and the comparison in the period-magnitude diagram (see Di Criscienzo et al. 2004).

In this paper we present results from the theoretical modeling of the observed $B$ and $V$ light curves of 14 RR Lyrae stars in the LMC, based on the detailed photometric study of the LMC RR Lyrae stars by C03 and Di Fabrizio et al. (2005, hereafter DF05). Our sample includes seven fundamental-mode (RRab) and seven first-overtone (RRc) pulsators that, according to the spectroscopic analysis of Gratton et al. (2004, hereafter G04), cover the metallicity range from $-2.12$ to $-0.79$ in [Fe/H], with an average value of $-1.54$ dex. The application of the method to a significant number of Population II pulsators in the same stellar system, namely, the LMC RR Lyrae stars, represents a powerful test of the inner consistency and predictive capability of the adopted theoretical scenario, providing at the same time an independent estimate of the LMC distance modulus and a direct comparison between Population I and II distance indicators, which strengthens our knowledge of the local distance scale.

The organization of the paper is as follows. In §2 we briefly discuss the adopted photometric (light curves and reddening values) and spectroscopic (metallicities) databases. In §3 we present the pulsation models, and the fit of the observed light curves and the derivation of the intrinsic stellar parameters (masses, luminosities, and effective temperatures) for both fundamental and first-overtone pulsators are described in §4. In §4 we also discuss the comparison with the intrinsic parameters predicted for the program stars by the evolutionary horizontal-branch (HB) models and by the Fourier decomposition of the visual light curves of the fundamental-mode RR Lyrae stars. The derived LMC distance modulus and the associated uncertainty are presented in §5, along with a discussion of the resulting RR Lyrae luminosity-metallicity relation. A summary of the results and some final remarks in §6 close the paper.

2. THE OBSERVATIONAL DATABASE

The RR Lyrae stars analyzed in the present paper were selected from the high-quality photometric catalog of variable stars in the LMC published by DF05. The catalog contains $B$, $V$, and $I$ light curves in the Johnson-Cousins photometric system of 162 variables located in two areas (referred to as fields A and B) close to the bar of the LMC, of which 135 are RR Lyrae stars. These variables were used by C03 to very carefully determine the distance of the LMC, getting the value $\mu_0(V_{LC}) = 18.515 \pm 0.085$ mag ($\sigma$ scatter of the mean) as the average of 17 independent methods based on Population I and II distance indicators. A large fraction of the RR Lyrae stars in DF05 were also analyzed spectroscopically by G04, who measured individual metal abundances for about 100 of them, using low-resolution spectra taken with the Focal Reducer/Low Dispersion Spectrograph at the Very Large Telescope.

The target stars were selected by visual inspection of the DF05 catalog, preferring objects with well-sampled and accurate light curves and a variety of morphologies, periodicities, and colors. We chose for our analysis a number of single-mode fundamental and first-overtone pulsators not affected by the Blazhko effect (Blazhko 1907) or other irregularities of the light variations. The selected objects all have evenly covered $B$ and $V$ light curves with about 60–70 data points in $V$ and about 40 in $B$ and with internal photometric accuracy of 0.02–0.04 mag in $V$ and 0.03–0.05 mag in $B$, according to DF05. The $I$ light curves in the DF05 catalog are generally of lower accuracy and have a rather limited number of data points (14–15); thus, we did not attempt fitting this band.

To ensure variety of the light-curve morphologies, we selected objects spanning a range in period from 0.487 to 0.656 days for the fundamental-mode and from 0.232 to 0.385 days for the first-overtone pulsators.

Metallicities [Fe/H] are available for all our targets, either from the spectroscopic analysis by G04 or estimated according to the Jurscik & Kovács (1996) method from the $\phi_{31}$ parameter of the Fourier decomposition of the visual light curves (see §§6 and 6.1 of DF05).

G04 spectroscopic metal abundances are tied to the metallicity scale defined by the Harris (1996) [Fe/H] abundances for the Galactic globular clusters M68 and NGC 1851 (see §4 in G04); on average, they are 0.06 dex more metal-rich than the Zinn & West (1984) scale. The “photometric” metallicities (star 9660 only) were transformed to the G04 scale according to the procedure described in §3.3 of C03. The metallicity range spanned by the selected targets (from $-2.12$ to $-0.79$ dex in [Fe/H] in the G04 scale) is large enough to check the luminosity-metallicity relation of the LMC RR Lyrae stars derived by other studies (e.g., C03 and G04), using the absolute magnitudes derived from the model fitting (see §5.1).

Following the selection criteria described above, we ended up having in our sample a number of RRab stars with relatively long periods ($P > 0.6$ days). One of them (star 9660) also has a relatively high metal abundance ([Fe/H] = $-1.5$ and, as confirmed by its rather red color ($(B-V) = 0.47$ mag), lies close to the red edge of the RR Lyrae instability strip. This is the object for which we have achieved the best satisfying model fitting (see §4 and Fig. 1). Indeed, as anticipated in §1, current pulsation models often fail to reproduce the morphology of the light curves of long-period fundamental-mode RR Lyrae stars close to the FRE. In fact, while the theoretical light curves are generally able to reproduce the sawlike shape with amplitude decreasing from the fundamental blue edge to the FRE of the observed fundamental-mode RR Lyrae stars, at the lowest effective temperatures the models also show a secondary peak before the phase of maximum light. This secondary peak is of increasing strength as the FRE is being approached. However, it is not present in the observed light curves.

C03 estimated the average reddening of the LMC fields containing our targets using the colors of the edges of the RR Lyrae instability strip. They derived $E(B-V) = 0.116 \pm 0.017$ mag for the field closer to the LMC bar (field A) and $E(B-V) = 0.086 \pm 0.017$ mag for the farther one (field B), corresponding to a differential reddening of 0.03 mag between the two areas. Our RRc sample includes two of the three variables that define the first-overtone blue edge (FOBE) of the RR Lyrae stars in C03 and DF05. C03 also estimated individual reddenings for the RRab variables using the Sturch (1966) method.
The method, which is based on the mean \(B - V\) colors at minimum light of the variables. The color excesses inferred from our model-fitting procedure can be directly compared with both average and individual reddenings in C03, thus providing an independent check of C03 values and hence of the distance for the LMC in that paper. This check is particularly relevant in light of the controversy existing regarding the actual reddening toward the LMC (see discussions in Udalski et al. 1999, hereafter U99; Zaritsky 1999; C03; Alcock et al. 2004, hereafter A04; Zaritsky et al. 2004) and is presented in §4.4.

The list of RR Lyrae stars analyzed in this paper is provided in Table 1 along with a summary of their relevant observed quantities. Namely, we list identifier, variable type and period, intensity-averaged mean \(M_V\) and \(M_B\) magnitudes with the related total uncertainties, number of data points and amplitudes of the light curves taken from DF05, metal abundances taken from G04, and reddenings taken from C03.

3. PULSATION MODELS

In the last few years an extensive and detailed set of updated nonlinear convective pulsation models of RR Lyrae stars has been developed covering wide ranges in period and metal abundances (see Bono et al. 2003; Marconi et al. 2003, and references therein). The physical and numerical assumptions adopted in the theoretical computations were widely discussed in these papers, to which the interested reader is referred for details.

The complete topology of the instability strip, where the blue boundaries for fundamental and first-overtone modes are connected to the position of the H and He ionization regions within the pulsating envelope and the red boundaries are due to the quenching produced by convection, as well as the variations of the relevant quantities (namely, luminosity and radial velocity) along the pulsation cycle. The capability to reproduce light and radial

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5 The total photometric errors associated with the mean \(M_V\) and \(M_B\) magnitudes are the sum in quadrature of the internal uncertainties, corresponding to the average residuals from the Fourier best-fitting models of the observed light curves as computed by GRATIS (Graphical Analyzer of Time Series; Di Fabrizio 1999; Clementini et al. 2000; see DF05), and of the contributions due to uncertainties of the photometric calibration (0.0175 and 0.032 mag in \(V\) and \(B\), respectively; C03 and DF05) and aperture corrections (0.018 and 0.019 mag in \(V\) and 0.032 and 0.014 mag in \(B\) in fields A and B, respectively; C03).
velocity curves allows us to directly compare observed and predicted variations. Note also that, as discussed in BCM00, in order to properly reproduce all the morphological features exhibited by the first-overtone curves, one needs models constructed by assuming a vanishing overshooting efficiency in the regions where the superadiabatic gradient attains negative values. All the models adopted in the present investigation are computed with this assumption of the treatment of turbulent convection and include an updated input physics (see BCM00 for details).

4. FIT OF THE OBSERVED LIGHT CURVES

In order to reproduce the observed light curves of the selected RR Lyrae stars, we adopted as input parameters the metal abundances and the periods reported in Table 1, and for each pulsator we computed isoperiodic model sequences (corresponding to the

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| Star | Type | Period (days) | $V_{\text{mean}}$ (mag) | $\sigma_f$ (mag) | $N_p$ | $\langle B \rangle$ (mag) | $\sigma_B$ (mag) | $N_p B$ (mag) | $A_r$ (mag) | $A_s$ (mag) | [Fe/H] |
|------|------|---------------|--------------------------|-----------------|------|-------------------------|----------------|----------------|--------------|--------------|---------|
| 5902 | ab   | 0.570         | 19.121                   | 0.033           | 54   | 19.472                  | 0.037          | 23             | 1.015        | 1.282        | -2.12   |
| 2525 | ab   | 0.616         | 19.340                   | 0.036           | 69   | 19.764                  | 0.063          | 41             | 0.991        | 1.272        | -2.06   |
| 7620 | ab   | 0.656         | 19.079                   | 0.040           | 70   | 19.409                  | 0.067          | 37             | 1.071        | 1.366        | -2.05   |
| 7477 | ab   | 0.656         | 19.183                   | 0.033           | 69   | 19.552                  | 0.057          | 40             | 1.108        | 1.371        | -1.67   |
| 2249 | ab   | 0.610         | 19.346                   | 0.041           | 69   | 19.775                  | 0.052          | 35             | 0.747        | 0.987        | -1.56   |
| 9660 | ab   | 0.622         | 19.392                   | 0.038           | 67   | 19.862                  | 0.054          | 41             | 0.669        | 0.811        | -1.50   |
| 7325 | ab   | 0.487         | 19.435                   | 0.035           | 68   | 19.845                  | 0.054          | 40             | 1.131        | 1.449        | -1.28   |
| 2024 | ab   | 0.360         | 19.500                   | 0.048           | 72   | 19.876                  | 0.059          | 40             | 0.509        | 0.606        | -1.92   |
| 4179 | c    | 0.356         | 19.173                   | 0.037           | 50   | 19.502                  | 0.048          | 29             | 0.438        | 0.560        | -1.53   |
| 8837 | c    | 0.316         | 19.566                   | 0.045           | 64   | 19.905                  | 0.059          | 41             | 0.501        | 0.631        | -1.52   |
| 2623 | c    | 0.291         | 19.368                   | 0.043           | 65   | 19.631                  | 0.064          | 40             | 0.441        | 0.595        | -1.34   |
| 27697| c    | 0.333         | 19.166                   | 0.041           | 66   | 19.541                  | 0.064          | 39             | 0.396        | 0.471        | -1.33   |
| 2517 | c    | 0.232         | 19.695                   | 0.049           | 69   | 19.925                  | 0.052          | 36             | 0.452        | 0.555        | -0.92   |
| 2119 | c    | 0.265         | 19.659                   | 0.052           | 64   | 19.986                  | 0.071          | 39             | 0.297        | 0.354        | -0.79   |

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*a* Star identifier, type, period, intensity-averaged mean magnitudes with the related uncertainties, number of data points, and amplitudes of the light variations are from DF05.

*b* Metallicities [Fe/H] are on the G04 metallicity scale.
observed periodicity) for the global metal abundance $Z$ inferred from the empirical $\frac{\text{Fe}}{H}/C_{138}$ value. Then for each model the theoretical $M_V$ versus phase curve was superposed to the data and shifted vertically in magnitude to match the observed behavior, by allowing at the same time the model input $Z$ to vary within the ranges permitted by the empirical determination. The necessary magnitude shift provides a direct evaluation of the apparent distance modulus of the selected objects.

Although the best-fit solution is searched for over a wide range of stellar parameters, the stellar masses were selected in order to cover at least the evolutionary predictions for HB stars of the corresponding metal abundances (see, e.g., Cassisi et al. 1998; Pietrinferni et al. 2004; D’Antona et al. 2002; V. Caloi 2005, private communication; Sweigart & Catelan 1998; Catelan et al. 1998; VandenBerg et al. 2000). For each adopted stellar mass, the model luminosity and effective temperature were then varied in order to simultaneously reproduce the period and the light-curve morphology in the $V$ band. To this purpose, for each model the predictedbolometric light curve was converted into the $B$ and $V$ bands adopting the model atmospheres of Castelli et al. (1997a, 1997b). When needed, the standard mixing-length value ($\ell/H_p = 1.5$) was increased to $\ell/H_p = 1.85 - 2.2$, again in the range of the values adopted in current evolutionary computations.

The best-fit models resulting from this investigation are shown in Figures 1 and 2 for the fundamental-mode and the first-overtone pulsators, respectively, and for both $V$ (left) and $B$ (right) light curves. The corresponding intrinsic stellar parameters, namely the stellar mass, luminosity, and effective temperature, are labeled for each pulsator (left) and summarized in Table 2, along with the input periods, the adopted global metallicities $Z$, and the mixing-length parameter choices. We find that the models that best reproduce the $V$-band light curves also show a good agreement with observations in the $B$ band. We also found that models corresponding to the spectroscopic metallicities (transformed to $Z$ values) were generally able to best fit the observed light variations. Only in the case of stars 5902 and 2517 did we have to decrease and increase, respectively, the input empirical metallicity to achieve a good reproduction of the observed light curves. However, these variations were always within the range allowed by the errors of the spectroscopic determinations.

The inferred apparent $V$ and $B$ distance moduli, $\mu_V$ and $\mu_B$, and their related uncertainties are reported in columns (9) and

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Fig. 2.—Results from the theoretical modeling of the $V$ (left) and $B$ (right) light curves of the first-overtone pulsators in our sample. Stars are ordered by increasing metallicity. For each variable we indicate the star identifier and period according to DF05, the global metal abundance $Z$ inferred from the $[\text{Fe}/H]$ values in G04 or DF05, and the mass, luminosity, and effective temperature obtained from the fit.

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We adopted the relation $\log Z = [\text{Fe}/H] - 1.7$, neglecting the possible occurrence of $\alpha$-enhancement phenomena.
derived from the difference \( \mu_B - \mu_V \) is given in column (11). True individual \( V \) distance moduli, \( \mu_0 \), evaluated from the model fitting and the observed curves but are completely independent of our knowledge of the variable star reddening and distance.

As shown in Figures 1 and 2, models are not able to completely reproduce the rising branch of some of the fundamental-mode pulsators. This is particularly true for the coolest pulsator in our sample, namely, variable star V9660, for which the appearance in the model light curve of a hump before the maximum light changes the slope of the rising branch and causes a delay of the phase of maximum itself. A similar effect is also present, although to a lesser extent, in the fitting of V2249 and

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\begin{array}{cccccccccccccc}
\text{Star} & \text{Type} & P & Z^a & \Delta H_p & M/M_\odot & \log L/L_\odot & T_e & \mu_V & \mu_B & E(B-V) & \mu_0 & <M_V> \\
\hline
5902 & ab & 0.570 & 0.0001 & 2.1 & 0.75 & 1.78 & 6700 & 18.81 & 0.060 & 18.87 & 0.062 & 18.519 & 0.080 & 0.347 & 0.060 \\
2525 & ab & 0.616 & 0.0002 & 1.9 & 0.75 & 1.78 & 6750 & 18.99 & 0.062 & 19.12 & 0.080 & 18.562 & 0.130 & 0.336 & 0.062 \\
7620 & ab & 0.656 & 0.0002 & 1.89 & 0.70 & 1.815 & 6660 & 18.87 & 0.064 & 18.97 & 0.084 & 18.579 & 0.074 & 0.252 & 0.064 \\
7477 & ab & 0.656 & 0.0004 & 1.85 & 0.67 & 1.78 & 6600 & 18.89 & 0.060 & 18.99 & 0.076 & 18.515 & 0.069 & 0.336 & 0.060 \\
2249 & ab & 0.610 & 0.0005 & 2.2 & 0.70 & 1.76 & 6625 & 18.99 & 0.065 & 19.12 & 0.072 & 18.658 & 0.121 & 0.392 & 0.065 \\
9660 & ab & 0.622 & 0.0006 & 2.0 & 0.68 & 1.73 & 6500 & 18.89 & 0.063 & 19.03 & 0.074 & 18.549 & 0.073 & 0.467 & 0.063 \\
7325 & ab & 0.487 & 0.001 & 2.0 & 0.62 & 1.65 & 6800 & 18.79 & 0.061 & 18.89 & 0.074 & 18.437 & 0.062 & 0.640 & 0.061 \\
2024 & c & 0.360 & 0.0002 & 1.5 & 0.665 & 1.73 & 7050 & 19.08 & 0.069 & 19.21 & 0.077 & 18.720 & 0.076 & 0.435 & 0.069 \\
4179 & c & 0.356 & 0.0006 & 1.5 & 0.70 & 1.73 & 7080 & 18.85 & 0.062 & 18.96 & 0.069 & 18.580 & 0.082 & 0.348 & 0.062 \\
8837 & c & 0.316 & 0.001 & 1.5 & 0.62 & 1.64 & 7100 & 18.95 & 0.067 & 19.06 & 0.077 & 18.590 & 0.068 & 0.637 & 0.067 \\
2623 & c & 0.291 & 0.001 & 1.5 & 0.63 & 1.63 & 7140 & 18.73 & 0.066 & 18.80 & 0.081 & 18.374 & 0.122 & 0.652 & 0.066 \\
27697 & c & 0.383 & 0.001 & 1.5 & 0.65 & 1.745 & 7031 & 18.80 & 0.065 & 18.93 & 0.081 & 18.440 & 0.072 & 0.376 & 0.065 \\
2517 & c & 0.232 & 0.004 & 1.5 & 0.60 & 1.53 & 7225 & 18.825 & 0.070 & 18.965 & 0.072 & 18.552 & 0.137 & 0.889 & 0.070 \\
2119 & c & 0.265 & 0.003 & 1.5 & 0.63 & 1.605 & 7220 & 18.96 & 0.072 & 19.06 & 0.087 & 18.600 & 0.080 & 0.705 & 0.072 \\
\end{array}
\]

\(^a\) The \( Z \) values were derived from the observed metal abundances [Fe/H] in Table 1, using the relation \( \log Z = [\text{Fe/H}] - 1.7 \).
V2525. Analogous problems were found by Castellani et al. (2002) in fitting with current pulsation models the fundamental-mode RR Lyrae stars at the FRE in the globular cluster ω Cent.

As for the first-overtone pulsators, the light curves become close to pure sinusoids as the FOBE is approached (see the case of variable V2119). This behavior holds for all the explored stellar masses and luminosity levels and might suggest the occurrence of some kind of degeneracy of the solution and the need for fixing an M-L relation. However, since the range of effective temperature covered by almost pure sinusoidal light curves is quite narrow (100–150 K) at each luminosity level, by selecting the stellar mass in the range of the evolutionary predictions for the adopted metal abundance, the best-fit mass and luminosity are constrained by the observed period and amplitude. We note, however, that the very short period, the low apparent luminosity, and the sinusoidal light curve of variable V2517 could also make it consistent with a fundamental-mode δ Scuti model (with stellar mass in the range 1.5–2.0 $M_\odot$), according to the predictions of Bono et al. (1997).

Finally, we point out that the mixing-length parameter adopted to fit the observed light curves has the standard value $\ell/H_P = 1.5$ for all the first-overtone pulsators, whereas it ranges from 1.85 to 2.2 for the fundamental-mode variables, again in agreement with previous results from the model-fitting technique.

4.1. Uncertainties of the Derived Intrinsic Quantities

In order to evaluate the uncertainties associated with the fitting procedure and their impact on the inferred intrinsic quantities, we have computed additional model sequences for a subsample of fundamental and first-overtone pulsators by varying the stellar parameters around the best-fit values. As a result of this procedure, we find mean uncertainties of $\delta \log T_{\nu}$ and $\delta \log L/L_\odot$ = 0.015, $\delta \log T_{\nu}$ = 25 K, and $\delta \log M/M_\odot$ = 0.02. These uncertainties contribute an error of $\sim$0.05 mag in the derived apparent distance moduli $\mu_V$ and $\mu_B$. Final errors on $\mu_V$ and $\mu_B$ should also include the contributions due to the photometric uncertainties of the observed light curves. These are provided in columns (S) and (O) of Table 1 and, once added in quadrature to the 0.05 mag uncertainty of the fitting procedure, lead to the total uncertainties of the observed light curves. These are provided in columns (E) and (F) of Table 2.

4.2. Comparison with the Intrinsic Parameters Predicted from the Evolutionary Models

Stellar masses and luminosities derived from the model fitting are generally consistent, within the uncertainties on the model fitting quoted in § 4.1, with the values predicted by stellar evolution models of the proper metal abundances. This is shown in Table 3, where the comparison is made with the evolutionary...
zero-age horizontal-branch (ZAHB) models of Cassisi et al. (1998) and Pietrinferni et al. (2004), D’Antona et al. (2002) and V. Caloi (2005, private communication), Sweigart & Catelan (1998) and Catelan et al. (1998), and finally VandenBerg et al. (2000). The comparison among estimates given by different authors helps us to quantify the uncertainty of current evolutionary predictions. For some of the variables we find that the pulsation model fitting provides significantly smaller masses and/or higher luminosity levels than all the considered ZAHB models, thus suggesting possible evolutionary effects. This is indeed the case for the metal-poor variable stars V5902, 7620, 7477, and 2024 VvedenBerg et al. (1998) and Pietrinferni et al. (2004), D’Antona et al. (2002) and Catelan et al. (1998); however, this is not reliable (see also the discussion in Cacciari et al. 2005).

In Table 4 the pulsational reddenings derived from the model fittings are compared with estimates obtained for the same stars or LMC regions by C03, U99, and A04 using different techniques. In particular, reddenings labeled “strip” (see col. [4] of Table 5) were obtained by C03 from the comparison of the colors of the edges of the RR Lyrae instability strip, defined by the variables contained in the two LMC fields they observed, with those of the low-reddening globular cluster M3. They determined two distinct values that apply to the variables contained in each given field separately. Reddenings labeled “Sturch” (see col. [5] of Table 5) are “individual” estimates derived by C03 using the Sturch (1966) method, which is based on the color at minimum light of the fundamental-mode RR Lyrae stars. U99 is the average reddening measured from variations in the I luminosity of clump stars located in OGLE-II field LMC_SC21. This field partially overlaps C03 field A, and according to Table 14 of DF05, two of the variable stars analyzed here (namely, the RRc stars 2119 and 27697) fall into the common region. Finally, A04 is the mean color excess estimated from 330 first-overturn RR Lyrae stars spread over 16 MACHO fields close to the LMC bar. We only have the RRc star 8837 in common with the A04 sample (see Table 12 in that paper).

As discussed in § 4, notwithstanding their large uncertainties, the pulsational reddenings provide a consistency check of the color excesses derived by other techniques. In this respect we note that they agree well with the empirical values by C03, while on average, they are around 0.02–0.03 mag smaller than the U99 and A04 estimates. However, this systematic difference is not surprising given the rather clumpy reddening of the LMC, the larger areas covered by the reddening indicators used in both U99 and A04, and their locations on or closer to the LMC bar than in C03.

In the following we adopt for each of our targets the weighted average of the pulsational, C03 strip, and C03 Sturch reddenings (values in cols. [3]–[5] of Table 5). These average values are provided in column (8) with their related uncertainties, which are simply the standard deviations of the weighted means. They are used together with the apparent distance moduli \( \mu_V \) in

4.4. Comparison of Reddening Estimates

The amount of reddening affecting the LMC still remains poorly known, since estimates by different techniques and authors have often provided controversial results that do not agree with each other (see U99; Zaritsky 1999; C03; A04; Zaritsky et al. 2004). The LMC color excess is also found to vary by large amounts from one region of the galaxy to the other, thus requiring local estimates that are to be preferred to the use of average values over large areas. The pulsational reddenings, being derived for each star individually, indeed provide estimates of the local reddening in the region containing the variable that can be directly compared to other local estimates of the \( E(B - V) \).

In Table 5 the pulsational reddenings derived from the model fittings are compared with estimates obtained for the same stars or LMC regions by C03, U99, and A04 using different techniques. In particular, reddenings labeled “strip” (see col. [4] of Table 5) were obtained by C03 from the comparison of the colors of the edges of the RR Lyrae instability strip, defined by the variables contained in the two LMC fields they observed, with those of the low-reddening globular cluster M3. They determined two distinct values that apply to the variables contained in each given field separately. Reddenings labeled “Sturch” (see col. [5] of Table 5) are “individual” estimates derived by C03 using the Sturch (1966) method, which is based on the color at minimum light of the fundamental-mode RR Lyrae stars. U99 is the average reddening measured from variations in the I luminosity of clump stars located in OGLE-II field LMC_SC21. This field partially overlaps C03 field A, and according to Table 14 of DF05, two of the variable stars analyzed here (namely, the RRc stars 2119 and 27697) fall into the common region. Finally, A04 is the mean color excess estimated from 330 first-overturn RR Lyrae stars spread over 16 MACHO fields close to the LMC bar. We only have the RRc star 8837 in common with the A04 sample (see Table 12 in that paper).

As discussed in § 4, notwithstanding their large uncertainties, the pulsational reddenings provide a consistency check of the color excesses derived by other techniques. In this respect we note that they agree well with the empirical values by C03, while on average, they are around 0.02–0.03 mag smaller than the U99 and A04 estimates. However, this systematic difference is not surprising given the rather clumpy reddening of the LMC, the larger areas covered by the reddening indicators used in both U99 and A04, and their locations on or closer to the LMC bar than in C03.

In the following we adopt for each of our targets the weighted average of the pulsational, C03 strip, and C03 Sturch reddenings (values in cols. [3]–[5] of Table 5). These average values are provided in column (8) with their related uncertainties, which are simply the standard deviations of the weighted means. They are used together with the apparent distance moduli \( \mu_V \) in

\[ \mu_V = \mu_V^{\text{DF05}} + D_m \]

Note.—Stars 2249 and 9660 have large maximum deviation (Dm) values: \( D_m \leq 4.769 \) and \( D_m \leq 3.746 \), respectively (see § 6 in DF05).
5. THE DISTANCE TO THE LMC

True distance moduli \( \mu_0 \) for our program stars were computed from the apparent moduli in column (9) of Table 2 and the reddening in column (8) of Table 5 using the standard extinction law \([A_V = 3.1(E(B-V))]\). They are provided in column (12) of Table 2. Errors in these \( \mu_0 \) values are the sum in quadrature of the uncertainties in the apparent distance moduli \( \mu_V \) and 3.1 times the uncertainty of the reddenings. By performing a weighted mean of these \( \mu_0 \) values, we obtain a final estimate for the true distance modulus of the LMC of \( \langle \mu_0 \rangle = 18.54 \pm 0.02 \) (\( \sigma = 0.09 \), standard deviation about the average of the 14 RR Lyrae stars). The 0.09 mag dispersion of this average value is fully accounted for by uncertainties in the reddening and model-fitting technique, implying that the distance moduli derived for individual objects are consistent within the respective error bars.

The derived LMC average distance modulus is well within the range of the most recent evaluations in the literature that all prefer the long distance scale (see Walker 2003; C03; Alves 2004, and references therein), agrees well with the results of the light-curve fitting of two classical Cepheids in the LMC by BCM02, and is in excellent agreement with the Keller & Wood (2002) LMC distance modulus from the model fitting of 20 LMC bump Cepheids. This excellent agreement between Population I and II distance indicators in the LMC is very rewarding in light of the long-standing controversy regarding the distance to the LMC based on these two independent indicators. Moreover the agreement with the Keller & Wood determination, which is based on a different pulsation code and relies on different physical and numerical assumptions, supports the soundness and reliability of our results.

We also point out that a different choice for the reddening, namely, adoption of U99 and A04 average values \([E(B-V)] = 0.142\) mag], would give \( \langle \mu_0 \rangle = 18.46 \pm 0.02 \), again in the range of the “long” scale and at odds with methods favoring much shorter distance moduli (in the range from \( \sim 18.2 \) to \( \sim 18.3 \) mag) for the LMC (e.g., Fernley et al. 1998a; Udalski 2000; Popowski 2001; Dambis 2003; Rastorguev et al. 2005).

5.1. The RR Lyrae Luminosity-Metallicity Relation

HB and RR Lyrae stars are known to follow a luminosity-metallicity relation generally considered to be of linear form. The slope of this relation is still a matter of debate, with values in the range from 0.30 (Sandage 1993) to 0.18–0.20 mag dex\(^{-1}\) (Caloi et al. 1997; Cassisi et al. 1998; Fernley et al. 1998b; C03; G04; Rich et al. 2001, 2005). There is also empirical and theoretical evidence for a nonlinearity of the relation followed by the Galactic globular clusters (Caputo et al. 2000; Rey et al. 2000); however, there is no clear proof of such a nonlinearity in the behavior of the Galactic (Fernley et al. 1998b) and LMC (C03, G04) field RR Lyrae stars, as well as in that of the M31 globular clusters (Rich et al. 2001, 2005). At fixed metal abundance there is also an intrinsic spread in the HB luminosity due to evolutionary effects (see, e.g., Sandage 1990). Such evolutionary effects are also predicted by evolutionary and synthetic HB computations (see, e.g., Lee et al. 1990; Caputo et al. 1993; Caloi et al. 1997; Cassisi et al. 2004 and references therein). A fairly large number of objects should be considered in order to reduce the impact of the evolutionary effects, since evolution off the ZAHB can affect the slope of the luminosity-metallicity relation.

C03 and G04 have recently derived the slope of the luminosity-metallicity relation of the LMC RR Lyrae stars using a fairly significant large sample of variables (98 stars) based on their homogeneous and accurate photometric and spectroscopic data sets for these stars. Since RR Lyrae stars in the LMC can, in the first approximation, all be considered at the same distance from us, C03 and G04 used directly the dereddened apparent visual magnitudes of the variables without any assumption of their absolute magnitudes, which might be affected by problems of zero point in the distance scale. Further advantages of the C03 and G04 approach were the significant statistics of their sample and the large number of objects at intermediate metal abundance; the metal distribution of C03 and G04 sample peaks at [Fe/H] = −1.48 dex, with the bulk of stars (66 objects) in the...
metallicity bin \(-1.7 < \text{[Fe/H]} < -1.3\). Both these characteristics allow minimization of the effects on the slope of the intrinsic spread in luminosity of the RR Lyrae stars due to their evolution off the ZAHB. They derived a rather mild slope of \(0.214 \pm 0.047 \text{mag dex}^{-1}\) in agreement with results from the Baade-Wesselink method of 28 Galactic field RR Lyrae stars \((\Delta M_{r}/[\text{Fe/H}] = 0.20 \pm 0.04 \text{mag dex}^{-1};\) Fernley et al. 1998b) and from the HB luminosity of 20 globular clusters in the Andromeda galaxy \((\Delta M_{r}/[\text{Fe/H}] = 0.20 \pm 0.09 \text{mag dex}^{-1};\) Rich et al. 2005).

We have combined the \(\langle M_{r} \rangle\) values derived from the model fitting (see col. [13] of Table 2) with the metallicities used in the fitting (see col. [4] of Table 2) to determine the slope of the luminosity-metallicity relation defined by the 14 LMC RR Lyrae stars in our sample. A simple linear fit provides a slope of \(\Delta M_{r}/[\text{Fe/H}] = 0.34 \text{mag dex}^{-1}\) using all objects and 0.28 mag dex\(^{-1}\) if star 2517, the object with rather unusually faint absolute magnitude, is discarded. The same linear regression using the corresponding dereddened apparent magnitudes \(V_{0}\) (obtained from the average \(\langle V \rangle\) values in col. [4] of Table 1 corrected for the reddenings in col. [8] of Table 5, assuming the standard extinction law) would give \(\Delta M_{r}/[\text{Fe/H}] = 0.31\) and 0.24 mag dex\(^{-1}\), respectively. All these values are higher than the slope derived by C03 and G04. However, since the \(V_{0}\) versus [Fe/H] fit also provides steeper slopes compared to the C03 and G04 values, this demonstrates that the difference is due to the sample selection and that it does not arise from errors in the absolute magnitudes obtained by the model fitting. Indeed, it should be kept in mind that the 14 LMC RR Lyrae stars analyzed in this paper represent less than 15% of the C03 and G04 sample and that although the peak of the fit metallicities of our RR Lyrae subsample \([\text{Fe/H}]_{*} = -1.53\) is very close to the average metallicity of the C03 and G04 total sample, our metallicity distribution is skewed toward low metal abundances. Moreover, the comparison with the ZAHB evolutionary predictions indicates the presence of evolutionary effects for almost all the metal-poor objects in our sample, and these effects are expected to cause a steepening of the slope. Thus, the higher slopes found here are simply the result of both the poorer statistics and the higher incidence of evolutionary effects in our sample compared with the C03 and G04 sample.

### 6. SUMMARY AND FINAL REMARKS

We have fitted the nonlinear convective pulsation models by Bono et al. (2003) and Marconi et al. (2003) to 14 LMC RR Lyrae stars with accurate photometry, metal abundances, and reddening estimates by DF05, G04, and C03. This is the first time that the model-fitting technique is applied to a significantly large number of RR Lyrae stars within the same stellar system, thus providing an important assessment of the predictive capabilities of the adopted theoretical pulsation models and, at the same time, a new independent estimate of the Population II distance to this fundamental first step on the astronomical distance ladder.

We have obtained \(\mu_{0}(\text{LMC}) = 18.54 \pm 0.02\), in very good agreement with the LMC “long” astronomical distance (Walker 2003; C03; Alves 2004). Masses, luminosities, and effective temperatures derived from the model fitting are in satisfactory agreement with the predictions of theoretical HB models, as derived from various authors in the literature. We note that such a detailed and punctual comparison of the results of pulsation model fitting and the evolutionary expectations had never been performed in the previous applications of the method to RR Lyrae stars. The pulsational reddenings are in good agreement with values in C03, thus further supporting the estimates in that paper and the soundness of the present approach.

Finally, note that our final result for the LMC distance modulus is in excellent agreement with the estimate provided by Keller & Wood (2002) on the basis of a similar method applied to 20 classical Cepheids in the same stellar system. This occurrence suggests that the results of the model-fitting technique are only marginally dependent on the adopted pulsation code, as well as on the physical and numerical assumptions in the model computations. It also shows that there is no discrepancy between the Population I and Population II distance scales to the LMC.

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### REFERENCES

Alcock, C., et al. 2004, AJ, 127, 334 (A04)
Alves, D. R. 2004, NewA Rev., 48, 659
Blazhko, S. 1907, Astron. Nachr., 175, 325
Bono, G., Caputo, F., Cassisi, S., Castellani, V., Marconi, M., & Stellingwerf, R. F. 1997, ApJ, 477, 346
Bono, G., Caputo, F., Castellani, V., Marconi, M., Storm, J., & dell’Innocenti, S. 2003, MNRAS, 344, 1097
Bono, G., Castellani, V., & Marconi, M. 2000, ApJ, 532, L129 (BCM00) ——, 2002, ApJ, 565, L83 (BCM02)
Bono, G., Marconi, M., & Stellingwerf, R. F. 1999, ApJS, 122, 167
Bono, G., & Stellingwerf, R. F. 1994, ApJS, 93, 233
Cacciari, C. 1999, in ASP Conf. Ser. 167, Harmonizing Cosmic Distance Scales in a Post-Hipparchus Era, ed. D. Egret & A. Heck (San Francisco: ASP), 110
Cacciari, C., Corwin, T. M., & Carney, B. W. 2005, AJ, 129, 267
Caloi, V., D’Antona, F., & Mazzitelli, I. 1997, A&A, 320, 823
Caputo, F., Castellani, V., Marconi, M., & Ripepi, V. 2000, MNRAS, 316, 819
Caputo, F., De RINALDIs, A., Manteiga, M., Pulone, L., & Quarta, M. L. 1993, A&A, 276, 41
Carretta, E., Gratton, R. G., Clementini, G., & Fusi Pecci, F. 2000, ApJ, 533, 215
Cassisi, S., Castellani, M., Caputo, F., & Castellani, V. 2004, A&A, 426, 641
Cassisi, S., Castellani, V., dell’Innocenti, S., & Weiss, A. 1998, A&AS, 129, 627
Castellani, V., dell’Innocenti, S., & Marconi, M. 2002, in ASP Conf. Ser. 265, \(\omega\) Centauri, A Unique Window into Astrophysics, ed. F. van Leeuwen, J. D. Hughes, & G. Pietro (San Francisco: ASP), 193
Castelli, F., Gratton, R. G., & Kurucz, R. L. 1997a, A&A, 318, 841 ——, 1997b, A&A, 324, 432
Catelan, M., Borissova, J., Sweigart, A. V., & Spassova, N. 1998, ApJ, 494, 265
Clementini, G., Gratton, R. G., Bragaglia, A., Carretta, E., Di Fabrizio, L., & Maio, M. 2003, AJ, 125, 1309 (C03)
Clementini, G., et al. 2000, AJ, 120, 2054
Dambis, A. K. 2003, in Galactic Dynamics, ed. C. Boily et al. (Les Ulis: EDP Sciences), 55
D’Antona, F., Caloi, V., Montalban, J., Ventura, P., & Gratton, R. 2002, A&A, 395, 69
Di Criscienzo, M., Marconi, M., & Caputo, F. 2004, ApJ, 612, 1092
Di Fabrizio, L. 1999, Laurea thesis, Univ. Bologna
Di Fabrizio, L., Clementini, G., Maio, M., Bragaglia, A., Carretta, E., Gratton, R. G., Montegriffo, P., & Zoccali, E. 2005, A&A, 430, 603 (DF05)
Di Fabrizio, L., et al. 2002, MNRAS, 336, 841
Fernley, J. A., Barnes, T. G., Skillen, I., Hawley, S. L., Hanley, C. J., Evans, D. W., Solano, E., & Garrido, R. 1998a, A&A, 330, 515
Fernley, J. A., Carney, B. W., Skillen, I., Cacciari, C., & Janes, K. 1998b, MNRAS, 293, L61
Freedman, W. L., et al. 2001, ApJ, 553, 47
Gratton, R. G., Bragaglia, A., Clementini, G., Carretta, E., Di Fabrizio, L., Maio, M., & Taribello, E. 2004, A&A, 421, 937 (G04)
Harris, W. E. 1996, AJ, 112, 1487
Jurcsik, J., & Kovacs, G. 1996, A&A, 312, 111
Keller, S. C., & Wood, P. R. 2002, ApJ, 578, 144
Lee, Y. W., Demarque, P., & Zinn, R. 1990, ApJ, 350, 155
Marconi, M., Caputo, F., Di Criscienzo, M., & Castellani, M. 2003, ApJ, 596, 299
Pietrinferni, A., Cassisi, S., Salaris, M., & Castelli, F. 2004, ApJ, 612, 168
Popowski, P. 2000, ApJ, 528, L9
Rastorguev, A. S., Dambis, A. K., & Zabolotskikh, M. V. 2005, in The Three Dimensional Universe with GAIA (Noordwijk: ESA), in press
Rey, S.-C., Lee, Y.-W., Joo, J.-M., Walker, A., & Baird, S. 2000, AJ, 119, 1824
Rich, R. M., Corsi, C. E., Bellazzini, M., Federici, L., Cacciari, C., & Fusi Pecci, F. 2001, in IAU Symp. 207, Extragalactic Star Clusters, ed. E. K. Grebel, D. Geisler, & D. Minniti (San Francisco: ASP), 140
Rich, R. M., Corsi, C. E., Cacciari, C., Federici, L., Fusi Pecci, F., Djorgovski, S. G., & Freedman, W. 2005, AJ, in press (astro-ph/0502180)
Sandage, A. 1990, ApJ, 350, 603
———. 1993, AJ, 106, 703
Stellingwerf, R. F. 1982, ApJ, 262, 330
Sturch, C. 1966, ApJ, 143, 774
Sweigart, A. V., & Catelan, M. 1998, ApJ, 501, L63
Tammann, G. A., Sandage, A., & Reindl, B. 2003, A&A, 404, 423
Udalski, A. 2000, ApJ, 531, L25
Udalski, A., Szymański, M., Kubiak, M., Pietrzyński, G., Soszyński, I., Woźniak, P., & Ziembinski, B. 1999, Acta Astron., 49, 201 (U99)
VandenBerg, D. A., Swenson, F. J., Rogers, F. J., Iglesias, C. A., & Alexander, D. R. 2000, ApJ, 532, 430
Walker, A. R. 1999, in Post-Hipparcos Cosmic Candles, ed. A. Heck & F. Caputo (Dordrecht: Kluwer), 125
———. 2003, in Stellar Candles for the Extragalactic Distance Scale, ed. D. Alloin & W. Gieren (Berlin: Springer), 265
Wood, P. R., Arnold, A., & Sebo, K. M. 1997, ApJ, 485, L25 (WAS97)
Zaritsky, D. 1999, AJ, 118, 2824
Zaritsky, D., Harris, I., Thompson, I. B., & Grebel, E. K. 2004, AJ, 128, 1606
Zinn, R., & West, M. J. 1984, ApJS, 55, 45