

DISTANCE TO THE LARGE MAGELLANIC CLOUD: THE RR LYRAE STARS¹

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ABSTRACT

New photometry and spectroscopy for more than a hundred RR Lyrae stars in two fields located close to the bar of the Large Magellanic Cloud (LMC) are used to derive new accurate estimates of the average magnitude, the local reddening, the luminosity-metallicity relation, and the distance to the LMC. The average apparent luminosity of the RR Lyraes with complete V and B light curves is $\langle V(RR) \rangle = 19.412 \pm 0.019$ ($\sigma = 0.153$), $\langle B(RR) \rangle = 19.807 \pm 0.022$ ($\sigma = 0.172$) in our field A (62 stars) and $\langle V(RR) \rangle = 19.320 \pm 0.023$ ($\sigma = 0.159$), $\langle B(RR) \rangle = 19.680 \pm 0.024$ ($\sigma = 0.163$) in our field B (46 stars). The average V apparent luminosity of the clump stars in the same areas is 0.108 and 0.029 mag brighter than the RR Lyrae level ($\langle V_{\text{clump}} \rangle = 19.304 \pm 0.002$ and 19.291 ± 0.003 , in field A: 6728 stars, and B: 3851 stars, respectively). Metallicities from low-resolution spectra obtained with the Very Large Telescope have been derived for 101 RR Lyrae stars, finding an average value of $[\text{Fe}/\text{H}] = -1.48 \pm 0.03$ ($\sigma = 0.29$, on the Harris metallicity scale). An estimate of the reddening within the two fields was obtained (1) from the Sturch method applied to the fundamental-mode pulsators (RRab's) with known metal abundance and (2) from the colors of the edges of the instability strip defined by the full sample of RR Lyrae variable stars. We obtained $E(B-V) = 0.116 \pm 0.017$ and 0.086 ± 0.017 mag in fields A and B, respectively, with a clear-cut indication of a 0.03 mag differential reddening between the two fields. We find that reddening in field A is 0.028 mag smaller than derived by OGLE-II in the same area. On average, the new reddenings are also 0.035 mag larger than derived from Cepheids with projected distances within 2° from the centers of our fields. The new metallicities were combined with the apparent average V_0 luminosities to determine the slope of the luminosity-metallicity relation for the RR Lyrae stars. We derived $\Delta M_V(\text{RR})/\Delta [\text{Fe}/\text{H}] = 0.214 \pm 0.047$, with no clear evidence for the change in slope at $[\text{Fe}/\text{H}] = -1.5$, as recently suggested by evolutionary/pulsation and horizontal-branch models.

The dereddened apparent average luminosity of the RR Lyraes defined by the present photometry is $\langle V(\text{RR}) \rangle_0 = 19.064 \pm 0.064$ at $[\text{Fe}/\text{H}] = -1.5$. When coupled with the absolute magnitude derived from the Baade-Wesselink and the statistical parallaxes methods ($M_V(\text{RR}) = 0.68 \pm 0.15$ and 0.76 ± 0.13 mag at $[\text{Fe}/\text{H}] = -1.5$), both methods known to favor the short distance scale, this value leads to distance moduli for the LMC of $\mu_{\text{LMC}} = 18.38 \pm 0.16$ and $\mu_{\text{LMC}} = 18.30 \pm 0.14$, respectively. If we use instead the absolute magnitude from the new main-sequence fitting of Galactic globular clusters from Gratton et al. [$M_V(\text{RR}) = 0.61 \pm 0.07$ mag at $[\text{Fe}/\text{H}] = -1.5$], we derive $\mu_{\text{LMC}} = 18.45 \pm 0.09$.

The average I apparent luminosity of the clump stars derived by the present photometry is $\langle I_{\text{clump}} \rangle = 18.319 \pm 0.002$ and 18.307 ± 0.003 , in field A ($\sigma = 0.190$, 6728 stars) and B ($\sigma = 0.184$, 3851 stars), respectively. These values, once corrected for our new reddening estimates, lead to $\langle I \rangle_0 = 18.12 \pm 0.06$ mag and move the clump distance modulus to the LMC to 18.42 ± 0.07 and 18.45 ± 0.07 when Udalski or Popowski metallicity- I -luminosity relations for the clump stars are adopted.

All these values are only 1σ shorter than provided by the Population I distance indicators and make it possible to reconcile the short- and long-distance scale on a common value for the distance modulus of the LMC of $\mu_{\text{LMC}} = 18.515 \pm 0.085$ mag.

Key words: distance scale — Magellanic Clouds — RR Lyrae variable — stars: oscillations — stars: variables: other — techniques: photometric — techniques: spectroscopic

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1. INTRODUCTION

The Large Magellanic Cloud (LMC) is widely considered a benchmark in the definition of the astronomical distance scale; however, no general consensus has been reached so far on its actual distance, and a dichotomy at a 0.2–0.3 mag level seems to persist between *short* and *long* distances to the LMC as derived from Population I and II indicators. Population I distance indicators tend to cluster around a *long* distance modulus for the LMC, in the range from 18.5 to 18.7 mag. An internal dichotomy is presented instead by the Population II indicators, with most indicators based on “field stars” (Baade-Wesselink [B-W] and statistical parallax methods, in particular), yielding a *short* distance modulus of 18.3, while indicators based on “cluster stars” (e.g., the main-sequence-fitting method: Gratton et al. 1997; Carretta et al. 2000b; Gratton et al. 2002; the globular clusters dynamical models; or the pulsational properties of RR Lyraes in globular clusters: Sandage 1993a) support a *longer* modulus in the range from 18.4 to 18.6. Indeed, the well-known discrepancy between *short* and *long* distance scales derived from old, Population II stars is still an unsolved issue (see, e.g., Gratton et al. 1997), in spite of the impressive improvements in measuring distances achieved thanks to the *Hipparcos* mission. The average difference between the two scales (0.25–0.30 mag) translates into a difference of about $3\text{--}4 \times 10^9$ yr in the corresponding age of the Galactic globular clusters and in turn in the age of the universe.

1.1. The RR Lyrae Distance Scale to the LMC

The distance to the LMC from Population II objects is finally founded on the luminosity of the RR Lyrae variables: observations provide the “apparent luminosity” of the LMC RR Lyraes: $m(\text{RR}_{\text{LMC}})$. Various techniques provide the absolute luminosity of the RR Lyraes: $M(\text{RR})$. Distance to the LMC simply follows from the well-known relation between apparent and absolute magnitudes. The first step actually includes two issues: (1) the derivation/use of a relation between the absolute luminosity of RR Lyrae stars and metallicity; and (2) the derivation of the apparent magnitude of RR Lyrae stars at a given metal abundance. Both issues are addressed in this paper with the help of new, photometric and spectroscopic data we have obtained for more than 100 RR Lyrae stars in the bar of the LMC.

Various estimates of the *apparent luminosity* of RR Lyrae stars in the LMC have existed so far, with small but significant differences, as follows: (1) Walker (1992a) published average luminosities in the Johnson system for RR Lyraes in seven clusters of the LMC; the mean dereddened apparent magnitude of these stars is 18.95 ± 0.04 mag (182 variables) at an average metal abundance of $[\text{Fe}/\text{H}] = -1.9$ and for an average reddening value of $\langle E(B-V) \rangle = 0.09$ mag. A slightly different value of 18.98 ± 0.04 mag (160 variables) and $\langle E(B-V) \rangle = 0.07$ mag is obtained if NGC 1841, a cluster suspected to be about 0.2 mag closer to us (Walker 1992a), is discarded. (2) The MACHO microlensing experiment has led to the discovery of about 8000 RR Lyraes in the bar of the LMC (Alcock et al. 1996, hereafter A96), among which 73 are double-mode pulsators (Alcock et al. 1997, hereafter A97). The average dereddened apparent magnitude of the RR Lyraes published by A96 for a subsample of 500 of these variables is 19.09 at $[\text{Fe}/\text{H}] = -1.6$ (the most frequent metallicity value in A96 spectroscopic abundances of 15 RR Lyraes in their sample) and for an

assumed reddening value of $E(B-V) = 0.1$. Recently, MACHO photometry has been recalibrated to the standard Johnson-Cousins photometric system (Alcock et al. 1999, hereafter A99) superseding all prior calibrations. Alcock et al. (2000, hereafter A00) present the color-magnitude diagram of 9 million stars (9M CMD) contained in 22 MACHO fields covering the LMC bar, and they also provide median luminosity and metallicity of about 680 RRab's: $V = 19.45$ mag, and $[\text{Fe}/\text{H}] = -1.6$, respectively, and the revised average luminosity of the A97 RRd's: $\langle V \rangle = 19.327 \pm 0.021$, based on the new photometric calibration. (3) A further estimate of the apparent dereddened average luminosity of RR Lyraes in the LMC comes from observations obtained during the second phase of the Optical Gravitational Lensing Experiment (OGLE-II, Udalski, Kubiak, & Szymański 1997). Udalski (1998a) quotes an apparent dereddened average luminosity of $\langle V_0(\text{RR}) \rangle = 18.86 \pm 0.04$ mag at an average metallicity of $[\text{Fe}/\text{H}] = -1.6 \pm 0.2$ (see Table 6 of Udalski 1998a) and for assumed reddening values in the range from $E(B-V) = 0.17$ to 0.20 mag (see Table 2 of Udalski et al. 1998) based on 104 RR Lyraes observed in OGLE-II fields LMC_SC14, 15, 19, and 20. This value was revised to $\langle V_0(\text{RR}) \rangle = 18.94 \pm 0.04$ mag (Udalski et al. 1999b), on the claim that extinction was slightly overestimated in Udalski (1998a). Extrapolating back from this revised $\langle V_0(\text{RR}) \rangle$, the new adopted $E(B-V)$ should be about 0.025 mag smaller than in Udalski (1998a). Udalski (2000b) has further revised the OGLE-II apparent dereddened average luminosity of the RR Lyrae in the LMC bar to $\langle V_0(\text{RR}) \rangle = 18.91 \pm 0.01$ mag, apparently based on the total sample of Lyrae variables detected by OGLE-II in the LMC bar, at $[\text{Fe}/\text{H}] = -1.6$ and for $E(B-V) = 0.143$ mag. These new $\langle V_0(\text{RR}) \rangle$ and reddening values are inconsistent with both Udalski (1998a) and Udalski et al. (1999b) for these quantities; we further note that if the 0.3 dex difference in metallicity between the Udalski (2000b) and Walker (1992a) samples is taken into account, Walker's RR Lyraes should be 0.06 mag brighter, and not 0.04 (or 0.07) mag fainter, than Udalski (2000b). Both authors claim that their photometric zero points are good to 0.02–0.03 mag, so this could suggest that Walker's reddening is too small or Udalski's too large by $E(B-V) = 0.03\text{--}0.04$ mag.

Estimates of the *absolute magnitude* of the RR Lyrae stars come from the B-W method (Liu & Janes 1990; Jones et al. 1992; Cacciari, Clementini, & Fernley 1992; Skillen et al. 1993; Fernley 1994) and from the *Hipparcos*-based statistical parallaxes (Fernley et al. 1998a; Tsujimoto, Miyamoto, & Yoshii 1998; Gould & Popowski 1998) applied to field RR Lyraes.

Fernley et al. (1998b) provide a summary of previous B-W analyses and discuss the slope and zero point of the RR Lyrae absolute magnitude–metallicity relation. They quote a zero point of $M_V(\text{RR}) = 0.98 \pm 0.15$ mag (at $[\text{Fe}/\text{H}] = 0.0$) and a mild slope of 0.18 ± 0.03 mag, given by the weighted average of the B-W slope (0.20 ± 0.04) and of results for eight globular clusters (GCs) in M31 observed with the *Hubble Space Telescope* (Fusi Pecci et al. 1996, 0.13 ± 0.07). However, analysis of an enlarged sample of 19 M31 GCs (Rich et al. 2001) now suggests a steeper slope of 0.22 mag dex $^{-1}$. An even steeper slope of 0.30 mag dex $^{-1}$ was found by Sandage (1993a) from the pulsational properties of RR Lyrae stars. Finally, a shallow slope of $\sim 0.18\text{--}0.22$ mag dex $^{-1}$ has been obtained from evolutionary HB

models (e.g., Caloi, D'Antona, & Mazzitelli 1997; Cassisi et al. 1998). Moreover, recent evolutionary/pulsation and HB models also suggest that the slope may not be unique in the metallicity range spanned by the Galactic GCs (Castellani, Chieffi, & Pulone 1991; Cassisi et al. 1998; Caputo 1997; Demarque et al. 2000), with two different regimes for metallicities below and above $[Fe/H] = -1.5$.

Statistical parallaxes lead to $M_V(RR) = 0.77 \pm 0.15$ mag at $[Fe/H] = -1.53$ (Fernley et al. 1998a), 0.69 ± 0.10 mag at $[Fe/H] = -1.58$ (Tsujimoto et al. 1998), and 0.77 ± 0.13 at $[Fe/H] = -1.60$ (Gould & Popowski 1998), but do not provide information on the slope of the $M_V(RR)$ - $[Fe/H]$ relation.

In the remaining part of this section we assume a value of $\Delta M_V(RR)/\Delta[Fe/H] = 0.2$ mag dex $^{-1}$ (which is supported by both the B-W and the new M31 results)⁵ to transform the above $M_V(RR)$ values to the average metallicity of the LMC RR Lyrae stars in our sample. This is assumed to be $[Fe/H] = -1.5 \pm 0.2$, which is the most commonly adopted average value for the RR Lyrae variables in the LMC, and it was confirmed by the ΔS metal abundances derived by Bragaglia et al. (2001) for six of the LMC RRD's in our sample. This metallicity is also consistent with A96, and with the average metal abundance we derived from low-resolution spectroscopy of about 80% of the RR Lyrae stars considered in this paper (see § 3.3 and Gratton et al. 2003).

We thus derive $M_V(RR) = 0.72 \pm 0.15$ mag as average of the B-W (0.68 mag at $[Fe/H] = -1.5$)⁶ and of the statistical parallaxes results (0.76 at $[Fe/H] = -1.5$). This value, when combined with Walker's apparent luminosity for the LMC cluster RR Lyraes leads to a distance modulus for the LMC of $\mu_{LMC} = 18.32$ (at $[Fe/H] = -1.5$ dex) in better agreement with the *short* distance scale. On the other hand, MACHO's revised value ($V = 19.45$ mag at $[Fe/H] = -1.6$) leads to a *longer* modulus of 18.44 mag for the LMC, but further complicates the scenario since it also seems to suggest that an intrinsic difference of ~ 0.1 mag might exist between field and cluster RR Lyraes. In fact, if allowance is given for the 0.3 dex difference in metallicity between Walker's and the A96/A00 samples and according to $\Delta M_V(RR)/\Delta[Fe/H] = 0.2$, A00's apparent luminosity for the field RR Lyraes is 0.12 mag *fainter* than Walker's apparent luminosity for the cluster variables.⁷ Finally, if the bright average magnitude proposed by Udalski (2000b) is correct ($\langle V_0(RR) \rangle = 18.91 \pm 0.01$ mag at $[Fe/H] = -1.6$), the distance modulus to the LMC would be as short as $\mu_{LMC} = 18.21$. This shows that simply considering different

⁵ We will return on the value of the slope of the luminosity-metallicity relation in § 5.2.

⁶ The B-W determination of the absolute luminosity of the Galactic field RR Lyraes is being revised in order to test the effects on this technique of the most recent model atmospheres (Kurucz 1995, at <http://cfa-www.harvard.edu/amdata/amdata/kurucz18/kurucz.html>; Castelli 1999; Canuto & Mazzitelli 1992) with various approximations in the treatment of convection, different values of turbulent velocity and more complete and accurate opacity tables, as well as the use of instantaneous gravity along the pulsation cycle. Preliminary results (Cacciari et al. 2000) give $M_V(RR) = 0.56$ mag, for one star at $[Fe/H] = -1.5$ (RR Cet); this is about 0.12 mag brighter than found from previous studies (e.g., Fernley et al. 1998b). A similar analysis is presently being performed on a larger sample of field RR Lyraes at $[Fe/H] = -1.5$ (Cacciari, Clementini, & Castelli 2003), and on RR Lyrae stars in the globular cluster M3.

⁷ Even with the steep slope of $\Delta M_V(RR)/\Delta[Fe/H] \sim 0.3$, supported by Sandage (1993a) there is still a -0.10 mag difference between Walker's and A00, and a $+0.13$ mag difference between Walker's and Udalski (2000b), reddening corrected, apparent luminosities for the LMC RR Lyraes.

recent determinations for the average magnitude of the RR Lyrae stars, the range in the distance modulus values for the LMC is larger than 0.2 mag. This situation is clearly unsatisfactory, and the issue requires further inquiry.

1.2. What May Cause These Differences in $\langle V_0(RR) \rangle$?

An intrinsic difference at ~ 0.1 – 0.2 mag level between the luminosity of HB stars in globular clusters and in the field was tentatively suggested by Gratton's (1998) calibration of the absolute magnitude of field horizontal-branch (HB) metal-poor stars with good parallaxes from *Hipparcos*. Sweigart's (1997) evolutionary models, which include some extra mixing of He and other heavy elements (C, N, O), might give some support to this hypothesis, since there is observational evidence for extra mixing in cluster red giants, but not among field stars (Gratton et al. 2000). However, Gratton's suggestion was tested qualitatively by Catelan (1998) and, recently and in a more quantitative way, by Carretta, Gratton, & Clementini (2000a) using the pulsational properties of a selected sample of field and cluster RR Lyraes. Their results show that field and cluster variables in our Galaxy cannot be distinguished in the $\Delta \log P_{\text{field-cluster}}$ - $[Fe/H]$ plane, so that the actual existence of a luminosity difference between field and cluster variables seems very unlikely.

Alternative explanations for the differences in the apparent luminosity of the LMC RR Lyraes found by Walker (1992a), A00, and Udalski (2000b) should be considered. We note the following:

1. That MACHO photometry is in nonstandard blue and red filters, which are very different from the Johnson passbands of Walker's cluster RR Lyrae photometry (see Fig. 1 of A99). A99 find that there is a systematic shift of $\Delta V \sim -0.035$ mag between MACHO and other literature data, with MACHO photometry being brighter (see Fig. 7 of A99). Additional concern also arises from the accuracy of the MACHO photometry at the limiting magnitude typical for the LMC RR Lyraes (19–20 mag); the problem is clearly shown in Figure 6 of A99. Comparison with MACHO is presented in § 2.2, and the problem is considered at length in Di Fabrizio et al. (2003, hereafter DF03), where we find that MACHO's photometric zero points, while apparently correct in some of their fields, appear to present a mismatch in others (see § 2.2).

Udalski et al. (1997) provide a detailed description of the instrumental setup of OGLE-II. They briefly mention the OGLE-II filter passbands and comment that, except for the ultraviolet filter, they are very close to the standard Johnson-Cousins *UBVRI* photometric system. Udalski et al. (2000) compared OGLE-II apparent magnitudes and colors for a few local standard stars in the field of NGC 1835 they have in common with Walker (1993). They found a mean difference of $\Delta V = -0.026 \pm 0.025$ mag (based on six stars, Walker's magnitudes being slightly brighter) and $\Delta(B-V) = -0.026 \pm 0.028$ (based on four stars, Walker's colors being bluer), but they also noted that, for stars redder than $(B-V) \sim 1.2$ mag, OGLE colors are redder by more than 0.1 mag. Udalski et al. (2000) attribute this discrepancy to the Walker *B*-band filter, which matches rather poorly the standard *B* band (the color coefficient of the transformation is about 1.2; see Walker 1992b). However, given the small number of objects in common between Walker (1993) and Udalski et al. (2000), any firm conclusion on the

comparison between the two photometries seems premature, particularly at red colors. This point is considered more extensively in DF03, where we conclude that OGLE-II systematically overestimates apparent luminosities for stars close to the limit of their B , V photometry, including RR Lyrae and clump stars.

2. It may be possible that, as a result projection effects combined with small number statistics, the globular clusters in Walker (1992a) sample are, on average, closer to us than the bar of the LMC. Indeed, Walker (1992a) assumed that the clusters were on the same plane as younger populations, based on similarity in kinematics (Schommer et al. 1992). However, this assumption may be questioned in view of the large scatter of the individual objects in the sky (see Fig. 1), and Walker himself cautions that at least one of the clusters in his sample (NGC 1841) could actually be about 10% closer to us.

3. A major crucial point is the actual reddening toward and inside the LMC. Walker (1992a; see his Table 1) derives reddening values by means of a number of methods in each cluster of his sample, including two techniques based on the pulsational properties of RR Lyraes, namely, the color of the edges of the instability strip and Sturch's (1966) method. These reddenings range from $E(B-V) = 0.03$ for the Reticulum cluster to $E(B-V) = 0.18$ for NGC 1841, with an average value of $E(B-V) = 0.09$ mag. However, in some clusters the adoption of such reddening values results in a too blue dereddened instability strip (NGC 1835), suggesting that in these cases the reddening may be overestimated. In other clusters (NGC 1786, NGC 1841) the strip may be not totally filled: reddening estimates are rather uncertain in these cases. A96 do not derive an independent reddening estimate, but simply assume $E(B-V) = 0.1$ mag, based on Bessel's (1991) reexamination of the reddening toward and inside the two Clouds.

Udalski (1998a) adopts an average reddening value of $E(B-V) = 0.185$ mag for his RR Lyrae sample, but Udalski

et al. (1999b) claim that this value is too high. They do not give the revised value, but, extrapolating back from the revised $\langle V_0(\text{RR}) \rangle$, the new adopted $E(B-V)$ should be about 0.16 mag. Udalski et al. (1999a) published reddening values for all the 21 LMC fields observed by OGLE-II. They range from $E(B-V) = 0.105$ to 0.201 mag with an average value of 0.143 ± 0.017 mag. This average value is 0.042 and 0.017 mag smaller than the reddenings adopted for the LMC RR Lyrae stars in Udalski (1998a) and Udalski et al. (1999b), respectively. Finally, we recall that the reddening value derived from Cepheids in the bar of the LMC is $E(B-V) = 0.07$ mag (Laney & Stobie 1994), i.e., ~ 0.02 – 0.03 mag smaller than Walker's and A96's, and about 0.07 mag smaller than Udalski (2000b). This would be enough to justify most of the spread observed in different distance scales. The work presented in this paper represents a step toward the solution of these inconsistencies.

2. OUR NEW DATA SETS

We have undertaken a photometric and spectroscopic observational campaign of two fields close to the bar of the LMC, using the 1.5 m Danish, the 3.6 m, and the VLT ESO telescopes. Within our program we have obtained (1) accurate B , V , and I photometric light curves directly tied to the Johnson-Cousins photometric system for 152 variable stars in these areas, among which are 125 RR Lyrae stars, and (2) low-resolution spectra for 101 of the RR Lyrae stars, among which are nine of A97's LMC double-mode pulsators, and for more than 300 clump stars. The main purposes of the observing program were (1) the definition of the average luminosity and (2) the measure of the metal abundance of RR Lyrae and clump stars in the LMC, in order to investigate the luminosity-metallicity and mass-metallicity (for double-mode pulsators) relations of the RR Lyraes, as well as the metallicity distribution of the clump stars in the LMC bar. The photometric data are presented in DF03.

Metal abundances for a first sample of six double-mode RR Lyrae stars were derived using the ΔS method (Preston 1959), and masses of the stars were estimated from new pulsational models and the Petersen diagram (Petersen 1973). The mass-metallicity distribution of the RR Lyraes in the LMC was found to be indistinguishable from that obtained from Galactic globular clusters, thus ruling out any intrinsic difference in mass that might induce intrinsic differences between field and cluster RR Lyraes. The results from this first spectroscopic study are described in Bragaglia et al. (2001). New spectroscopic metal abundances for a sample comprising 80% of the RR Lyrae stars discussed in the present paper were obtained with FORS at the VLT in 2001 December. The metallicity derivation technique is briefly outlined in § 3.3 and described in detail in Gratton et al. (2003).

The present paper is devoted to the presentation of the results obtained from the combination of the photometric and spectroscopic study of the RR Lyrae stars. The new photometry has allowed us to define a very precise average apparent luminosity for the RR Lyrae stars in the bar of the LMC, which can be compared with Walker's (1992a) estimate for the LMC cluster RR Lyraes, as well as to the mean apparent luminosity of the LMC clump stars found in the same fields. These data also allow an independent estimate of the reddening in these regions of the LMC bar,

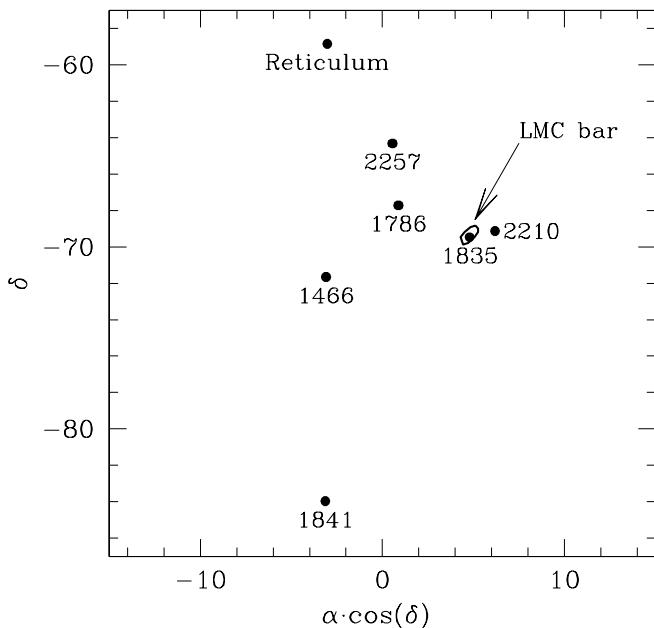


FIG. 1.—Positions of the seven LMC globular clusters studied by Walker (1992a) with respect to the LMC bar.

with fundamental fallbacks on the derivation of the distance to the LMC. The individual metallicities are combined with the apparent V_0 luminosities to firmly establish the slope of the luminosity-metallicity relation for RR Lyrae stars.

The photometric and spectroscopic data sets used in this paper are briefly described in §§ 2.1, 2.2, and 2.3, where we also provide a summary of the results from the comparison of our, MACHO, and OGLE-II photometries, based on large samples of stars in common between the three independent databases. The properties of the RR Lyrae variables in our sample (apparent average luminosity, period, and metallicity distributions) are discussed in § 3. Section 4 addresses the problem of measuring the reddening in the LMC, and it presents new estimates of $E(B-V)$ from the color of the edges of the instability strip defined by our RR Lyrae sample and from Sturch's method applied to the RRab's with known metal abundances. In § 5 we summarize our results on the RR Lyrae average luminosity and on the LMC reddening, and present the luminosity-metallicity relation defined by the RR Lyrae stars in our sample, based on our new photometric and spectroscopic analyses. Comparison with Walker (1992a), MACHO, and OGLE-II average luminosity of the LMC RR Lyrae stars is presented in § 6, where we also briefly review the use of the clump as a distance indicator and compare the average luminosity of the RR Lyrae stars with the luminosity distribution of the clump stars in the same areas. Finally, in § 7 we summarize our results and discuss the impact of the present new photometry, spectroscopy, and reddening values on the derivation of the distance to the LMC.

Photometric data, variable star identification, and period search procedures, as well as the detailed comparison between our, MACHO, and OGLE-II photometries, are fully described in DF03, where we publish the photometric catalog with multicolor light curves and the individual measurements for all the variable stars in our sample. Spectroscopic data, along with a detailed description of the metallicity derivation technique and the individual spectroscopic metallicities derived for the RR Lyrae stars, are presented in Gratton et al. (2003), where we also provide details on the derivation of the RR Lyrae luminosity and metallicity distribution of clump stars, based on the spectroscopic database obtained with the VLT, is postponed to a following paper in preparation.

2.1. The Photometric Data Set

The photometric data set used in this paper arises from observations taken with the 1.54 m Danish telescope (La Silla, Chile) in two separate observing runs, in 1999 January (four nights) and 2001 January (two nights), respectively. We observed at two different positions, hereafter called field A and B, close to the bar of the LMC and contained in fields 6 and 13 of the MACHO microlensing experiment. Field A is also about 40% overlapped with the OGLE-II field LMC_SC21 (Udalsky et al. 2000). In the 1999 run observations were done in the Johnson-Bessel B and V filters (ESO 450 and 451; see <http://www.ls.eso.org>), and we obtained 58 V and 27 B frames for field A, and 55 V and 24 B frames for field B. In the 2001 run observations were done in the Johnson-Bessel-Gunn B , V , and i filters (ESO 450, 451, and 425), and we

obtained 14 V , 14 B , and 14 i frames for field A, and 15 V , 14 B , and 14 i frames for field B. Both nights of the 2001 run were photometric, with good seeing conditions, while only one of the nights in 1999 was photometric.

Reduction and analysis of the 1999 photometric data were done using the package DoPHOT (Schechter, Mateo, & Saha 1993). Photometric reductions of the 2001 data were done using DAOPHOT/ALLSTAR II (Stetson 1996) and ALLFRAME (Stetson 1994). A detailed description of the reduction procedures can be found in DF03.

In the 2001 run nights were superior to the ones in the 1999 run, and a much larger number of standard stars were observed. Therefore, our entire photometric data set was tied to the standard Johnson-Cousins photometric system through the absolute photometric calibration of the 2001 run. Calibration equations are provided in DF03. They are based on 127 measurements in two separate nights of 27 standard stars selected from Landolt (1992)-Stetson (2000) standard fields PG 0918+029, 0231+051, 1047+003, and SA98, with magnitude and colors in the ranges $12.773 < V < 17.729$, $-0.273 < B-V < 1.936$, $-0.304 < V-I < 2.142$. Photometric zero-point accuracies are of 0.02 mag in V and 0.03 mag in B and I , respectively.

Variable stars were identified on the 1999 time-series data set using the program VARFIND, written for this purpose by P. Montegriffo. Candidate variable objects picked up interactively from the scatter diagram produced by VARFIND were checked for variability using the program GRATIS (Graphical Analyzer Time Series), a private software developed at the Bologna Observatory by P. Montegriffo, G. Clementini, and L. Di Fabrizio. Confirmed variable stars were then counter-identified on the 2001 frames, using private software by P. Montegriffo (see DF03 for further details.)

We detected 152 variable objects in the two fields and an additional seven candidate variable objects of unknown type. Of the certain variables 125 are of RR Lyrae type (115 single-mode and 10 double-mode RR Lyraes, one of which not previously known from A97). Of course, the high fraction of RR Lyrae stars among the identified variable stars is due to the type of observations and variable stars search we made.

Periods for all the identified variable stars were defined using the program GRATIS on the instrumental differential photometry with respect to stable, well-isolated objects used as reference stars. Thanks to the 2 year baseline of our observations, we were able to: (1) derive periods and epochs for all the 152 variables accurate to better than the fourth to fifth decimal place; the accuracy depends on the light curve data sampling, which in the best cases is 72 V , 41 B , 14 I data points for variables in field A, and 70 V , 38 B , 14 I data points for variables in field B; (2) identify the Blazhko modulation of the light curve (Blazhko 1907) in about 15% of our RR Lyrae stars; and finally (3) to derive complete and well-sampled B and V light curves for about 95% of the RR Lyrae stars. Typical accuracies⁸ for the single-mode, non-Blazhko variables are 0.02–0.03 mag in V , and 0.03–0.04 mag in B .

⁸ Accuracies are the average residuals from the Fourier best fitting models of the light curves.

Apart from RR Lyraes, we also fully covered the light curve of four anomalous Cepheids, nine eclipsing binaries with short orbital period ($P < 1.4$ days), six classical Cepheids, and reasonably well sampled the light curves of the other five Cepheids.

Examples of the light curves of an ab-, c-, and d-type RR Lyrae, as well as of an anomalous Cepheid, a classical Cepheid, and an eclipsing binary in our sample, are shown in Figures 2 and 3. The full catalog of individual photometric measurements and light curves is provided in DF03.

The location of the variable stars on the HR diagram of field A and B is shown in Figures 4 and 5, respectively, where they are plotted according to their intensity-averaged magnitudes and colors, and with different symbols corresponding to the various types.

2.2. Comparison with MACHO and OGLE-II Photometries

Our fields are contained in MACHO's fields 6 and 13, and there is about 40% overlap between field A and OGLE-II field LMC_SC21. This occurrence has allowed us to make a detailed comparison between our, MACHO, and OGLE-II photometries, based on large samples of stars and without any assumption about reddening.

The comparison with MACHO was restricted only to the variable stars in common, since calibrated photometry of individual stars was readily available only for the variable star subsample. We found that we have about 30% and 20% more short-period variables ($P < 4$ days) than MACHO in field A and B, respectively. We also found that MACHO

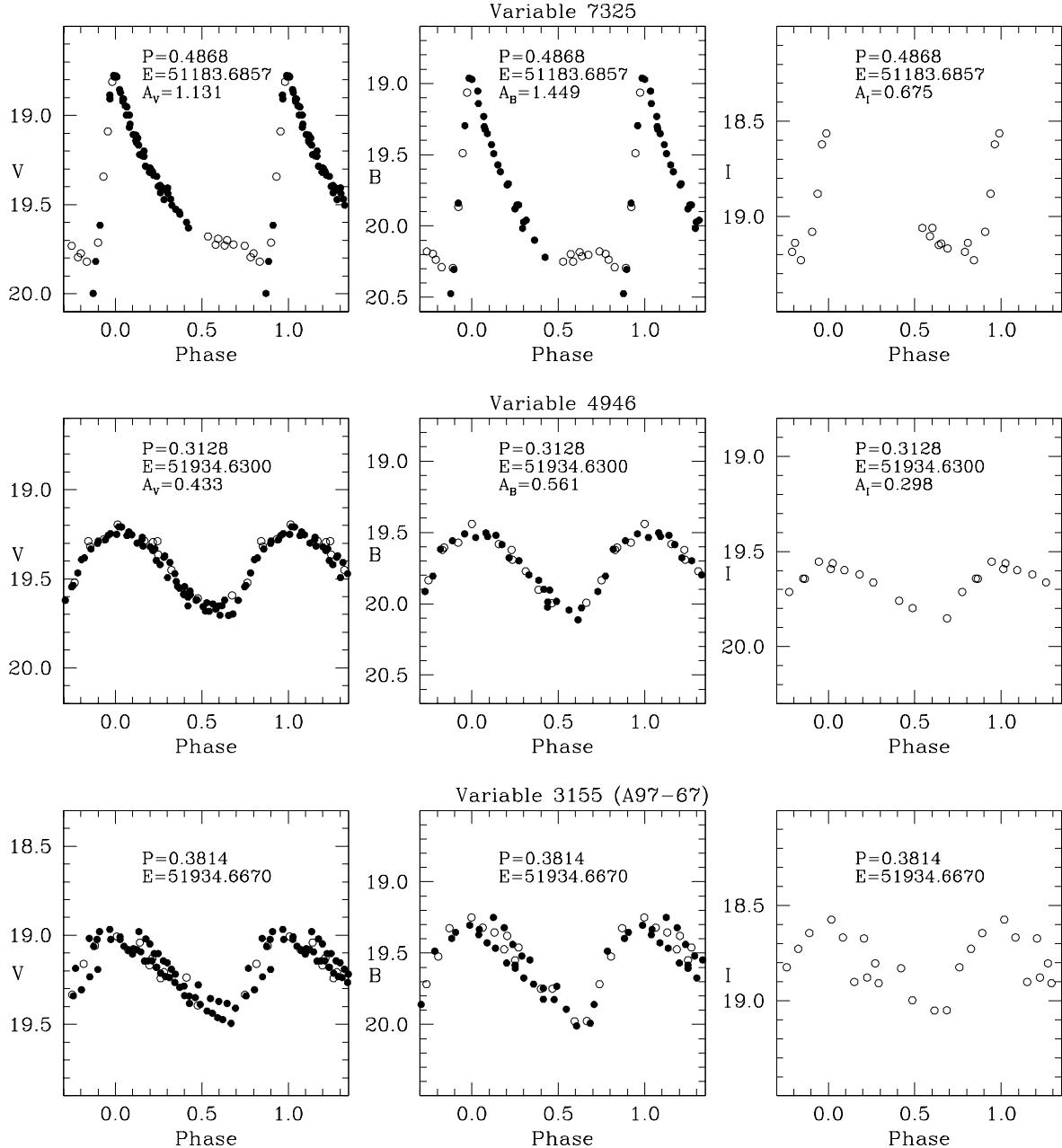


FIG. 2.— V , B , I light curves of RR Lyrae stars falling in our fields. Top to bottom: RRab, RRc, and RRd variable. Filled and open symbols are used for the 1999 and 2001 data, respectively.

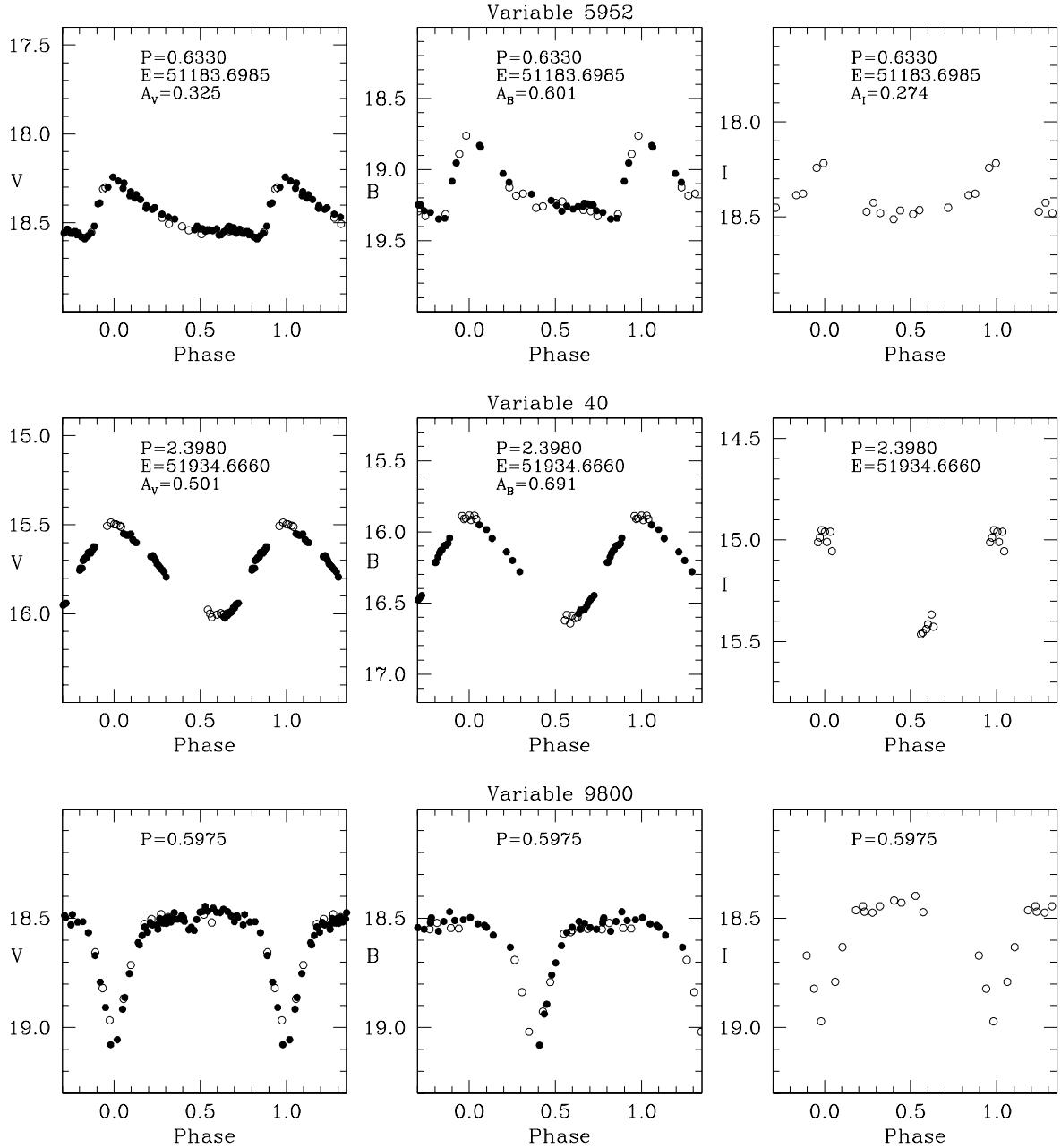


FIG. 3.— V , B , I light curves of an anomalous Cepheid, a classical Cepheid, and an eclipsing binary falling in our fields. Symbols are as in Fig. 2.

classification of some of the variable stars in common did not match our classification (see details in DF03).

The average V difference, in the sense present photometry minus MACHO, is -0.174 mag ($\sigma = 0.092$, 58 stars) in field A and -0.010 mag ($\sigma = 0.085$, 40 stars) in field B. The quite large systematic shift found for variable stars in field A, with MACHO luminosities being *fainter* than ours, is rather surprising and of no obvious explanation, since the different treatment of the background in the reduction package used by MACHO (SoDoPhot) is expected to produce *brighter* magnitudes than DAOPHOT+ALLFRAME photometry (A99). Moreover, we notice (1) that a shift by $+0.174$ mag of field A photometry would result in an average luminosity of the RR Lyrae stars in this area about 0.24 mag fainter than A00's median luminosity of the RRab's in the LMC, and (2) given the good agreement existing in field B, it would

imply a rather unlikely difference of about 0.27 mag in the average luminosity of RR Lyrae stars in the two fields.

Our field A is 42.13% overlapped with OGLE-II field LMC_SC21. In this common area we measured 21,524 objects (in all three photometric bands), our limiting magnitude reaches about 1.5 mag fainter, and we resolved about 39%, 26%, and 22% more stars (in B , V , and I , respectively) than OGLE-II.

There are about 13,000 objects in common between the two photometries, with V magnitude in the range from 16 to about 22.5 mag. Among these objects OGLE-II reports 114 variable stars; 96 of them have a counterpart in our database, but only 14 are identified as variable stars in our photometry. On the other hand, in the same area we have 22 further variable stars all having a counterpart, but not recognized as variable objects by OGLE-II. A more significant

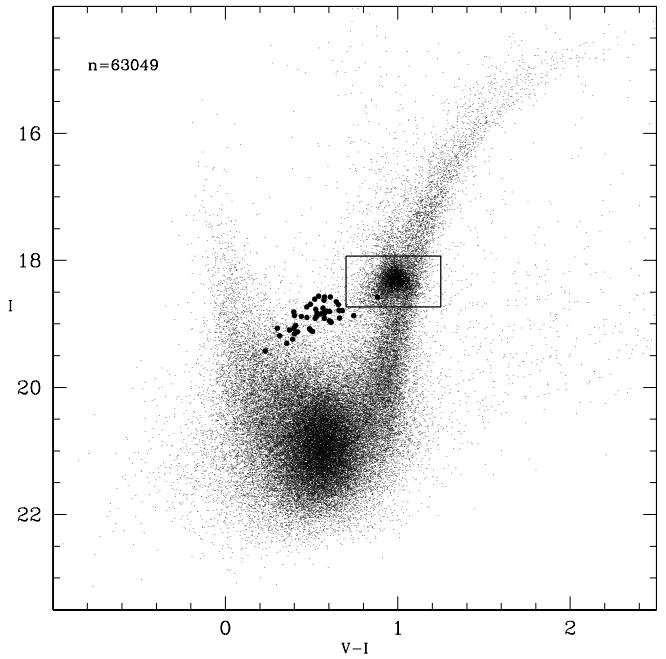
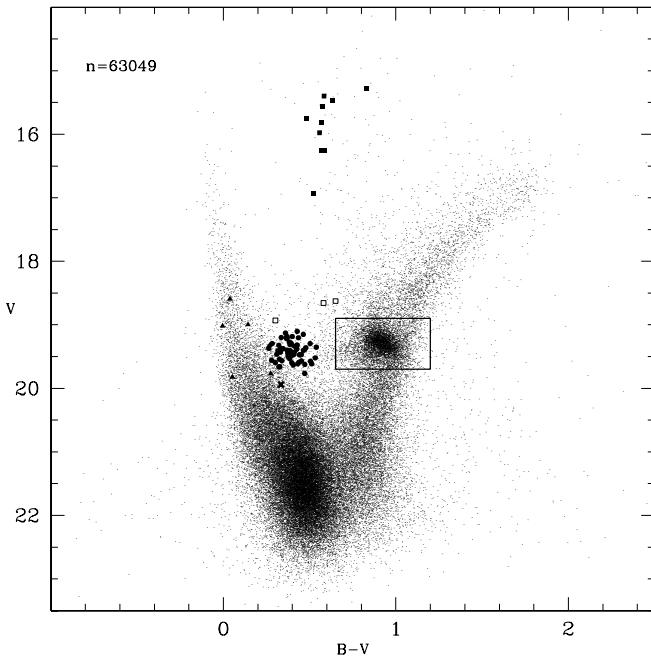


FIG. 4.— V vs. $B-V$, and I vs. $V-I$ color-magnitude diagrams of field A (R.A. = $05^{\text{h}}22^{\text{m}}43^{\text{s}}9$, decl. = $70^{\circ}34'15''$) from the ALLFRAME reduction of the 2001 data. The box outlines the clump stars of this field. Different symbols mark the variables identified in this field (RR Lyrae stars: filled circles; anomalous Cepheids: open squares; Cepheids: filled squares; binaries: filled triangles; δ Scuti: crosses), which are plotted according to their intensity-averaged magnitudes and colors. Only the RR Lyrae stars are shown in the I vs. $V-I$ diagram.

comparison with OGLE-II can be achieved by restricting the sample to the stars in common that have photometric errors smaller than 0.1 mag in all photometric passbands in both databases (about 5400, 6500, and 7200 stars in V , B , and I , respectively). Average residuals between the two photometries were computed dividing objects in magnitudes bins; they are provided in Table 5 of DF03. At the magnitude level of RR Lyrae and clump stars ($V \sim 19.4$, $B \sim 19.8$, $I \sim 18.8$; and $V \sim 19.3$, $B \sim 20.2$, $I \sim 18.3$,

respectively) offsets are: $\Delta V = 0.06$ ($\sigma_V = 0.03$), $\Delta B = 0.03$ ($\sigma_B = 0.04$), $\Delta I = 0.07$ ($\sigma_I = 0.05$), and $\Delta V = 0.06$ ($\sigma_V = 0.03$), $\Delta B = 0.03\text{--}0.04$ ($\sigma_B = 0.04\text{--}0.05$), $\Delta I = 0.07$ ($\sigma_I = 0.04\text{--}0.05$), with our photometry being systematically fainter than OGLE-II DoPhot photometry. This is not unexpected, since DoPhot is reported to give systematically brighter magnitudes for faint stars in crowded regions than DAOPHOT and since we resolve many more faint stars than OGLE-II in the area in common.

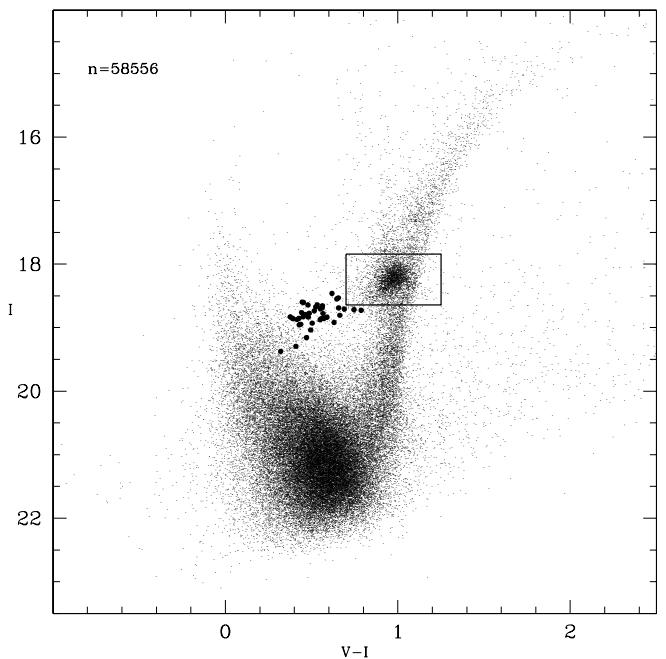
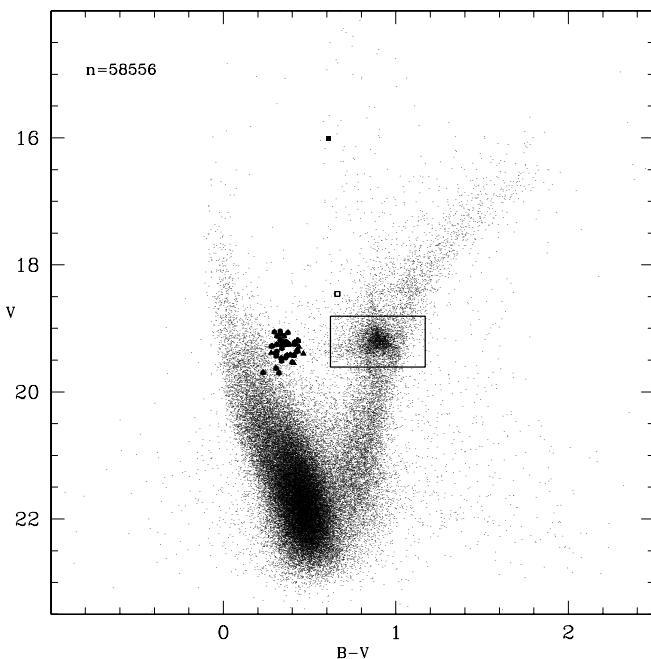


FIG. 5.—Same as Fig. 4 for field B (R.A. = $05^{\text{h}}17^{\text{m}}27^{\text{s}}9$, decl. = $71^{\circ}00'14''$)

The interested reader is referred to DF03 for a thorough discussion of the comparison with MACHO and OGLE-II photometries.

2.3. The Spectroscopic Data Set

Low-resolution spectra ($R \sim 450$) at minimum light for six of the double mode pulsators in our sample were obtained in 1999 January, with the Faint Object Spectrograph and Camera of the 3.6 m ESO telescope. We used the classical ΔS method (Preston 1959) to measure [Fe/H] abundances, as fully described in Bragaglia et al. (2001).

A more extended spectroscopic survey was conducted in 2001 with FORS at the VLT. We obtained low-resolution spectra ($R \sim 815$) for 80% of the RR Lyrae stars discussed in this paper and for about 300 clump stars. Metal abundances for the RR Lyrae stars were obtained using a revised version of the ΔS technique: we estimated metallicities for individual stars by comparing directly the strength of H lines and the K Ca II line with analogous data for RR Lyrae stars in three Galactic globular clusters of known metal abundance (namely, NGC 1851, M68, and NGC 3201). An advantage of this technique is that we do not need an explicit phase correction; even if accuracy of our [Fe/H] determinations is still a function of phase (as represented by the strength of the H lines): determinations accurate to about 0.2 dex are obtained only from observations taken far from maximum light. Note, however, that the allowed phase range is about 2 times larger than that required for a safe application of the original ΔS method. A detailed description of the metallicity derivation technique can be found in Gratton et al. (2003).

3. THE RR LYRAE STARS

3.1. The Apparent Luminosity

The average apparent luminosities of Lyraes with full coverage of the V and B light curves are $\langle V \rangle = 19.412 \pm 0.019$ ($\sigma = 0.153$, 62 stars), $\langle B \rangle = 19.807 \pm 0.022$ ($\sigma = 0.172$, 62 stars) in field A; and $\langle V \rangle = 19.320 \pm 0.023$ ($\sigma = 0.159$, 46 stars), $\langle B \rangle = 19.680 \pm 0.024$ ($\sigma = 0.163$, 46 stars) in field B. The I light curve coverage is inferior, being based only on the 2001 data, and we do not expand further on this band.

The double-mode RR Lyrae stars in our sample are slightly overluminous compared with the single-mode pulsators: $\langle V_{\text{RRd}} \rangle = 19.394 \pm 0.066$ ($\sigma = 0.161$, six stars), and $\langle V_{\text{RRd}} \rangle = 19.239 \pm 0.085$ ($\sigma = 0.171$, four stars), in field A and B, respectively. A similar result is found also by A96/A00.

There is a difference of 0.092 and 0.127 mag, respectively, between the average V and B magnitudes of the RR Lyrae stars in the two fields, explained by a difference in the reddening toward the two areas, with field A being 0.03 mag more reddened than field B (see § 4). A few RR Lyraes were discarded when calculating the above average values. These were 11 objects (four RRc and four RRab in field A, and two RRc and one RRab in field B), for which systematic offsets were present between the 1999 and 2001 light curves, possibly due to not resolved blends in either of the two data sets; variable stars whose light curves were not evenly covered (two stars in field A and three in field B); and one object in field A, which fell on a bad CCD column in the 1999 run.

The intrinsic dispersions of the average B and V apparent luminosities (and, in turn, of the average B and V absolute magnitudes) of the RR Lyraes in the two fields are: $\sigma_B \sim 0.17$ and $\sigma_V \sim 0.16$ mag, respectively. A number of sources contribute to form these dispersions:

1. the internal photometric errors of the present photometry: 0.02 mag standard deviation of the average;
2. the metallicity distribution of the RR Lyraes in our sample. The dispersion around the mean value of $[\text{Fe}/\text{H}] = -1.48$ found from the VLT low-resolution spectroscopy of 101 RR Lyrae stars in the sample is $\sigma = 0.29$ dex (see § 3.3 and Gratton et al. 2003). This metallicity dispersion well compares with the ~ 0.4 dex dispersion we would derive taking into account the total period distribution spanned by the ab-type RR Lyraes in our sample (0.40–0.74 days). According to $\Delta M_V(\text{RR})/\Delta[\text{Fe}/\text{H}] = 0.2$ mag dex $^{-1}$, these metallicity dispersions correspond to a magnitude dispersion of about 0.06 mag.
3. the level of evolution off the zero-age horizontal branch (ZAHB) of the variables in our sample. Here what matters is not the global systematic difference between ZAHB and average luminosity of the RR Lyraes, but rather the dispersion around the average RR Lyrae luminosity due to the evolution off the ZAHB of each individual RR Lyrae. Sandage (1990) studied the vertical height of the HB of a number of globular clusters of different metallicity and found for M3 and NGC 6981, clusters whose metallicity is close to the average value of the LMC, HB luminosities with standard dispersions of 0.064 and 0.097 mag, respectively, giving an average value of 0.08 mag⁹.
4. and, finally, the intrinsic depth of the observed fields.

Adding up in quadrature all dispersion contributions except the latter, we obtain a total dispersion of about 0.10 mag, to compare with the observed V dispersion of 0.16 mag. This gives us some hint on the actual intrinsic depth of our observed fields, for which we derive a most probable value of 0.13 and an upper limit of about 0.15 mag, corresponding to a dispersion in depth of 6.5% and 7.5% or 3.3 kpc and 3.8 kpc (for an assumed distance modulus $\mu_{\text{LMC}} = 18.50$ mag; see § 7).

Based on the spatial density profile of the MACHO RRab stars and on data for six additional fields from Kinman et al. (1991), A00 conclude that the majority of the old and metal-poor LMC field stars are likely to lie in a disk with $i = 35^\circ$, line of nodes running north-south, and center near the optical center (Westerlund 1997), and not in a spheroid. Our results on the intrinsic depths of field A and B are not in contrast with A00 results.

The comparison of the apparent luminosity of our RR Lyrae sample with other estimates available in the literature (Walker 1992a; Udalski et al. 2000; Udalski 2000b, and A00) is postponed to § 6.

We have formed $\langle B \rangle - \langle V \rangle$ and $\langle V \rangle - \langle I \rangle$ colors from the intensity average B , V , and I magnitudes for all the variables with complete light curves. These intensity average magnitudes and colors ($\langle V \rangle$, $\langle B \rangle - \langle V \rangle$, $\langle I \rangle$, $\langle V \rangle - \langle I \rangle$) were used to

⁹ This is likely to be an overestimate of the real contribution due to evolution, because the field RR Lyrae population should be dominated by stars closer to the ZAHB than variables in clusters at same metallicity (see Carney et al. 1992)

place the variables on the color-magnitude diagrams of the two fields, shown in Figures 4 and 5.

3.2. The Period Distribution

Two peaks are clearly visible in the period distribution of the single-mode RR Lyraes in our sample (115 objects), corresponding to the c- (38 objects) and the ab- (77 objects) type pulsators (see Fig. 8 of DF03). The number of c-type pulsators divides almost equally among the two fields (20 and 18 RR_c's in fields A and B, respectively). On the other hand, the number of RR_{ab}'s is about 50% larger in field A. This difference, although not statistically significant, may suggest that we could be missing some c-type pulsators in field A, likely because of the smaller amplitude of the variables and the larger crowding of the field.

The mean period of the c- and ab-type RR Lyraes is $\langle P_{RR_c} \rangle = 0.327$ days ($\sigma = 0.047$, 38 stars) and $\langle P_{RR_{ab}} \rangle = 0.580$ days ($\sigma = 0.064$, 77 stars), respectively, to be compared with 0.342 and 0.583 days of A96.

A96, on the basis of their $\langle P_{RR_{ab}} \rangle = 0.583$ days, conclude that the preferred period of the ab-type variables of the LMC falls between the periods of the Galactic RR Lyrae stars of Oosterhoff (1939) type I (Oo I) and II (Oo II), but it is actually closer to the Oo I cluster periods (being $\langle P_{RR_{ab}} \rangle = 0.55$ and 0.65 days in the Oo I and II clusters, respectively). This finding is confirmed and strengthened by our results.

The period-amplitude diagram of MACHO Bailey diagram sample (935 RRabs, see § 4.2 of A00), is found to be very similar to the ridge line defined by the RR_{ab}'s in M3, from which A00 infer similarity of the mean metallicity of the Bailey sample with M3. B and V amplitudes (A_B , A_V) were calculated for all the RR Lyraes in our sample with full coverage of the light curve as the difference between maximum and minimum of the best-fitting models (see DF03) and have been used together with the newly derived periods to build period-amplitude diagrams. The overlap in the transition region between ab and c type is small (six objects) and the transition period between c and ab type occurs in our sample at $P_{tr} \sim 0.40$ days, while $P_{tr} = 0.457$ days in A96. The period-amplitude distributions of the LMC variables were compared with the relations defined by the ab-type RR Lyraes in the globular clusters M3, M15, and ω Cen. RR Lyraes in field B seem to better follow the amplitude-period relations of the variables in M3 and to belong to the OoI type. Variables in field A, instead, have pulsational properties more intermediate between the two Oostheroff types (see Fig. 9 of DF03).

According to A97, nine double-mode pulsators were expected to fall in the observed areas. We actually detected all of them and also found evidence for one possible additional RRd candidate not previously known from A97: star 2249 (see Table 5 of DF03).

3.3. The Metallicity Distribution

Metal abundances derived by Bragaglia et al. (2001) for a first subset of six of the double-mode pulsators in our sample using Preston (1959) ΔS technique range from -1.09 to -1.78 , with an average value of $[Fe/H] = -1.49 \pm 0.11$ (six stars, rms = 0.28 dex), on the Clementini et al. (1995) metallicity scale, quite similar to the Zinn & West (1984) scale (see § 4 of Bragaglia et al. 2001).

Metallicities obtained from the spectroscopic survey conducted in 2001 with FORS at the VLT, for 101 of the RR Lyrae stars discussed in this paper range from ~ -0.5 to ~ -2.1 with an average metal abundance of $[Fe/H] = -1.48 \pm 0.03$ ($\sigma = 0.29$, 101 stars; see Gratton et al. 2003). These metallicities are tied to Harris (1996) metal abundances for the Galactic globular clusters NGC 1851, NGC 3201, and M68 that we used as calibrators. The values we have used¹⁰ are $[Fe/H] = -1.26$, -1.48 , and -2.06 , respectively, to compare with -1.33 , -1.56 , and -2.09 of Zinn & West (1984). Thus, they are on a metallicity scale that, on average, is 0.06 dex more metal-rich than the Zinn & West scale.

Photometric metallicities from the parameters of the Fourier decomposition of the V light curves were also derived for 29 RR_{ab}'s in our sample, six of which do not have spectroscopic metal abundances, applying techniques from Jurcsik & Kovács (1996) and Kovács & Walker (2001) (see DF03 for details). These metal abundances are on the metallicity scale defined by Jurcsik (1995), which is, on average, about 0.2 dex more metal-rich than the Harris (1996) scale. The average metallicity of this subsample of stars is $[Fe/H] = -1.27$ ($\sigma = 0.35$, 29 stars), in good agreement with the average values derived from the above spectroscopic analyses, once differences between metallicity scales are taken into account. The comparison between photometric and spectroscopic abundances can be found in Gratton et al. (2003).

The spectroscopic abundances also well compare with both the range and the most frequent value of A96 spectroscopic analysis of 15 LMC RR_{ab}'s, thus confirming both the similarity with M3 suggested by A00 and the existence of RR_{ab}'s that are very metal poor, which, according to A00, might trace a spheroid population.

4. THE REDDENING OF THE LMC

Accurate corrections for interstellar reddening are crucial for precise distance estimates. On the other hand, there is strong evidence that the reddening within the LMC is patchy and varies from one region to the other. This is the source of quite a lot of confusion in the various distance determinations to the LMC.

4.1. Literature Values

Bessel (1991) provides a reexamination of the reddening of the LMC obtained by several independent methods and concludes that the foreground $E(B-V)$ reddening probably lies between 0.04 and 0.09 mag, while the average reddening within the LMC is probably about 0.06 mag, but with many regions with higher and lower than average reddening.

Walker (1992a) derives reddening values ranging from 0.03 to 0.18 mag for the seven clusters he analyzes, based on a combination of several independent methods and estimates, as follows: (1) Burstein & Heiles (1982) maps; (2) the position of the red giant branch in the color-magnitude diagram of the clusters [the so called $(B-V)_{0,g}$ method]; (3) the pulsational properties of the variables in his sample [namely, the Sturch (1966) method applied to the ab-type RR Lyraes at minimum light and with $E(B-V) = 0.00$ mag for the

¹⁰ Available at <http://www.physun.physics.mcmaster.ca/Globular.html>.

reddening at the polar caps; and the colors of the edges of the instability strip defined by the RR Lyraes in each individual cluster of his sample].

The reddening maps (based on COBE/DIRBE and *IRAS* data) of Schlegel, Finkbeiner, & Davis (1998) give a foreground reddening, measured from dust emission in an annulus surrounding the LMC, of $E(B-V) = 0.075$. Schlegel et al. find that their reddenings are offset by $E(B-V) = +0.02$ mag with respect to those provided by Burstein & Heiles (1982), which are based on H I column densities and deep galaxy counts.¹¹ The same maps give upper limits of $E(B-V) = 0.218$ and 0.128 for field A and B, respectively. However Schlegel et al. maps do not provide reliable reddening for extended objects like the Clouds or M31 close to their centers.

Foreground and internal reddenings have also been estimated from *UBV* photometry of individual early-type stars by Oestreicher, Gochermann, & Schmidt-Kaler (1995) and Oestreicher & Schmidt-Kaler (1996). The values for the directions of our two fields are $E(B-V) = 0.056$ and 0.062 (foreground), and 0.150 and 0.140 (internal). We may then derive lower and upper limits of the reddening of $0.056 < E(B-V) < 0.206$ and $0.062 < E(B-V) < 0.202$ for field A and B, respectively. However, Zaritsky (1999) noted that reddenings derived from early-type stars may be biased toward large values, likely because these stars are preferentially located near star-forming regions.

Udalski et al. (1999a) published reddening values determined along 84 lines of sights for all of the 21 LMC fields observed with OGLE-II. They used the red clump stars for mapping the fluctuations of mean reddening in their fields, treating the mean *I*-band magnitude as the reference brightness. Differences of the observed *I*-band magnitudes of the red clump stars were assumed as differences of the mean A_I extinction and transformed into differences of $E(B-V)$ reddening assuming the standard extinction curve $E(B-V) = A_I/1.96$ by Schlegel et al. (1998). We note that this procedure neglects possible systematic differences in the intrinsic mean *I*-band luminosity of the LMC red clump due to age or metallicity variations from field to field of the LMC. As discussed in § 6.2, this may be a too crude assumption. The zero points of OGLE-II reddening maps were based on determinations around two LMC star clusters, namely, NGC 1850 [$E(B-V) = 0.15 \pm 0.05$ mag, based on *UBV* photometry by Lee 1995], and NGC 1835 [$E(B-V) = 0.13 \pm 0.03$ mag, based on colors of RR Lyr stars, Walker 1993],¹² and on determinations based on OB stars in the field of the eclipsing variable star HV2274 (Udalski et al. 1999a).¹³ These reddenings range from $E(B-V) = 0.105$ to 0.201 mag, with an average value of 0.143 ± 0.017 mag. This average value is, respectively, 0.042 and 0.017 mag lower than the reddenings adopted for

the LMC RR Lyrae in Udalski (1998a) and Udalski et al (1999b).

Much smaller reddenings are obtained by considering individual Cepheids. Reddenings for a total number of 80 individual Cepheids have been published by Caldwell & Coulson (1986) and Gieren, Fouqué, & Gomez (1998). These are the values used by Laney & Stobie (1994) and most other works on Cepheids. The two sets of reddenings are on the same system, and are coincident for the majority of the stars in common. These Cepheids have distances from the centers of our fields ranging from $0^{\circ}66$ up to $7^{\circ}8$. In Table 1 we give identification number and reddening value in both Caldwell & Coulson (1986) and Gieren et al. (1998) systems, for a subsample of Cepheids with projected distances within two degrees from either of the centers of our fields. An average of these reddening values gives $E(B-V) = 0.067 \pm 0.006$ mag (seven stars) and $E(B-V) = 0.067 \pm 0.023$ mag (15 stars) for field A and B, respectively. A weighted average of the reddening estimates (with weights proportional to the inverse square of the projected distance from our fields) for all Cepheids within the two samples yields mean reddening values of $E(B-V) = 0.070$ for field A and 0.063 for field B. Note also that a star-by-star comparison shows that the reddening for the Cepheids is on average ~ 0.06 mag smaller than the value given by Schlegel et al.'s maps.

Which of these different reddening scales should we adopt?

Independent indications for the reddening values in our fields can be derived directly from the properties of RR Lyrae variables in our sample; i.e., (1) from the colors at minimum light of the ab-type pulsators through the so-called Sturch method (Sturch 1966) and (2) from the colors of the edges of the instability strip defined by the full sample of RR Lyrae stars.

TABLE 1
REDDENING VALUES FOR CEPHEIDS WITHIN 2° FROM THE CENTERS
OF EITHER OF OUR FIELDS

HV Number	$E(B-V)^a$	$E(B-V)^b$	$d(A)$ (deg)	$d(B)$ (deg)
12823	0.058	...	0.93	1.30
2549	0.058	...	1.13	0.99
2527	0.070	...	1.18	0.66
12797	0.070	...	1.57	1.09
2694	0.070	...	1.67	2.05
6065	0.070	...	1.82	3.11
2749	0.070	...	1.92	2.49
2405	0.070	...	2.15	1.54
909	0.058	...	2.66	0.88
2352	0.100	0.105	2.71	0.96
2338	0.040	0.036	2.74	0.96
902	0.070	...	2.82	1.02
900	0.058	...	3.03	1.33
914	0.070	...	3.17	1.95
881	0.030	...	3.56	1.73
2257	0.060	0.061	3.74	1.95
873	0.130	...	3.75	1.92
878	0.058	...	3.76	1.97

^a Gieren et al. 1998.

^b Caldwell & Coulson 1986.

¹¹ On average, the reddenings of Schlegel et al. agree quite well with those usually adopted for the Galactic globular clusters (see data set by Harris 1996) for reddening values smaller than 0.10 mag; for more reddened clusters, the reddenings by Schlegel et al. are systematically larger by 30%.

¹² We recall however that the instability strip of NGC 1835 dereddened according to this $E(B-V)$ value appears too blue.

¹³ The value of $E(B-V) = 0.149 \pm 0.015$ used by Udalski et al. for this star has been questioned by Nelson et al. (2000), and Groenewegen & Salaris (2001), who suggested lower values of $E(B-V) = 0.088 \pm 0.025$ and 0.103 ± 0.007 , respectively.

Before applying these methods to our fields, we note that a direct comparison suggests that field A is more reddened than field B. In fact,

1. on average, RR Lyraes in field A are fainter by ~ 0.09 mag in V , and ~ 0.13 mag in B , compared with the variables in field B;

2. average colors of the ab-, and c-, and d-type RR Lyraes in field A are redder (by 0.036 and 0.016 mag, respectively).

We conclude that reddening is likely to be 0.03 ± 0.01 mag larger in field A than in field B. Such a difference is not inconsistent with the literature results mentioned above and will be used in the following discussion when combining results from the two fields.

4.2. Reddening from Sturch's Method

Sturch (1966) derives the reddening of *ab* type RR Lyraes from the (magnitude-averaged) color at minimum light ($B-V$)_{min} (phases 0.5–0.8), the period P , and the metal abundance [Fe/H] of the variables. The application of Sturch's method requires the knowledge of the metallicity of each individual RRab. We have used Sturch's method as described in Walker (1990, 1998), where the reddening zero point has been adjusted to give $E(B-V) = 0.0$ mag at the Galactic poles and the [Fe/H] is that of the Zinn & West (1984) metallicity scale, whereby

$$E(B-V) = (B-V)_{\text{min}} - 0.24P - 0.056[\text{Fe}/\text{H}]_{\text{ZW}} - 0.336$$

Metal abundances are available for 56 of the ab-type RR Lyrae stars from our VLT spectroscopic study. They are given in the upper portion of Table 2 (col. [5]), along with

TABLE 2—Continued

ID (1)	Field (2)	$\langle B-V \rangle_{\text{min}}$ (mag) (3)	P (days) (4)	[Fe/H] (5)	$E(B-V)$ (6)
15387	A	0.512	0.5598	-1.81	0.146
16249	A	0.480	0.6048	-1.86	0.106
18314	A	0.526	0.5871	-1.71	0.148
19450	A	0.537	0.3979	-0.90	0.159
19711	A	0.361	0.5530	-1.68	-0.010
25301	A	0.576	0.5606	-1.40	0.187
25362	A	0.509	0.5775	-1.49	0.121
25510	A	0.525	0.6496	-1.63	0.127
26525	A	0.601	0.5229	-1.63	0.234
26821	A	0.554	0.5875	-1.37	0.157
26933	A	0.456	0.4883	-1.34	0.081
28293	A	0.483	0.6615	-1.74	0.089
1408	B	0.453	0.6260	-1.70	0.065
1575	B	0.541	0.6739	-1.61	0.136
1907	B	0.524	0.5805	-1.52	0.137
2249	B	0.526	0.6104	-1.56	0.134
2884	B	0.515	0.6194	-1.90	0.140
3400	B	0.504	0.4862	-1.45	0.136
4780	B	0.576	0.6176	-1.20	0.162
4859	B	0.486	0.5234	-1.44	0.108
5902	B	0.459	0.5698	-2.12	0.108
6440	B	0.407	0.4948	-1.19	0.032
6798	B	0.498	0.5841	-1.20	0.092
7063	B	0.516	0.6543	-1.49	0.109
7442	B	0.519	0.5780	-1.58	0.136
7620	B	0.480	0.6562	-2.05	0.104
10811	B	0.500	0.4764	-1.42	0.132
14449	B	0.523	0.5841	-1.70	0.145
19037	B	0.505	0.4113	-1.26	0.144
22917	B	0.485	0.5647	-1.34	0.092
23502	B	0.525	0.4722	-1.43	0.159
24089	B	0.474	0.5598	-1.31	0.080
5167	A	0.514	0.6302	-1.32	0.115
8220	A	0.562	0.6768	-1.03	0.140
9660	A	0.496	0.6218	-1.35	0.100
3054	B	0.433	0.5080	-0.94	0.048
3412	B	0.522	0.5302	-1.62	0.158
4540	B	0.472	0.5689	-1.40	0.091

^a Metal abundances in the upper portion of the table derive from our spectroscopic study and are on the Harris 1996 metallicity scale (see § 3.3 and Gratton et al. 2003). Metal abundances in the lower portion of the table were derived from the Fourier parameters of the light curve and are on the Jurcsik 1995 metallicity scale. Reddenings were calculated using the relation given in § 4.2, after having transformed metallicities to the Zinn & West 1984 scale.

magnitude-averaged colors at minimum light (col. [3]) and periods (col. [4]) of the variables. These metallicities are on the Harris (1996) scale (see Gratton et al. 2003, and § 3.3). Reddenings for these stars have been calculated from the above relation after having offset all metallicities by -0.06 dex, to put them on the Zinn & West (1984) scale. For six additional objects (listed in the lower portion of Table 2), metal abundances on the Jurcsik (1995) scale were derived from the Fourier decomposition of the V light curves. We have used the relation provided by Jurcsik (1995; $[\text{Fe}/\text{H}]_{\text{Jurcsik}} = 1.431[\text{Fe}/\text{H}]_{\text{ZW}} + 0.880$) to transform metallicities to the Zinn & West scale.

Derived $E(B-V)$ values are given in col. [6] of Table 2. The average reddening value for the stars in field A is $E(B-V) = 0.133 \pm 0.005$ ($\sigma = 0.031$, average of 37 stars),

discarding star 19711, which gives a negative reddening value, and star 26525, which deviates more than 2.5σ from the average. The average value for the stars in field B is $E(B-V) = 0.115 \pm 0.007$ ($\sigma = 0.036$, average of 23 stars), again suggesting the existence of differential reddening between the two areas (~ 0.02 mag).

Walker (1998) found that Sturch's method gives reddening values systematically larger by 0.02–0.03 mag when compared to other reddening determination techniques. We have verified Walker's finding applying Sturch's method to some of the RR Lyrae stars in two of the clusters used as spectroscopic calibrators, namely M68 and NGC 1851. Brocato et al. (1994) have published B , V CCD photometry of RR Lyrae stars in M68. For three RRab's in their sample (namely, stars V9, V10, and V12) Sturch's method gives $E(B-V)_{V9} = 0.040$, $E(B-V)_{V10} = 0.039$, and $E(B-V)_{V12} = -0.011$, and an average value $E(B-V) = 0.04$, discarding V12, which gives a negative reddening. This average reddening is to be compared with literature values in the range from 0.02 to 0.04 mag (see Brocato et al. 1994, and reference therein), and with $E(B-V) = 0.035$ from Schlegel et al. (1998) maps. For NGC 1851 we have used Walker (1998) photometry for the RRab's V1, V6, V7, V11, V12, V16, V17, and V22. The average reddening from Sturch's method applied to these eight stars is $E(B-V) = 0.055$ ($\sigma = 0.012$, eight stars), to compare with $E(B-V) = 0.02$ by Harris (1996) and 0.061 mag from Schlegel et al.'s maps. The present results confirm that Sturch's method may overestimate reddening by 0.01–0.02 mag; therefore, we conclude that the reddening values for field A and B derived with Sturch's method can be considered as upper limits of the actual reddenings in these areas.

4.3. Reddening from the Colors of the Instability Strip

Reddening in our fields may be better constrained by comparing the edges of the instability strip defined by the RR Lyrae stars with those defined by variables in globular clusters of known $E(B-V)$. This same procedure was used by Walker (1992a) to estimate the reddening value in some of the LMC globular clusters.

Walker (1998) presents dereddened (magnitude-averaged) $B-V$ instability-strip boundary colors from precise observations of nine Galactic and LMC globular clusters covering a range in metallicity from –1.1 to –2.2

dex. The dereddened color of the blue edge is at $(B-V)_0 = 0.18 \pm 0.01$ mag, with no discernible dependence on metallicity, while the color of the red edge shows a shift of 0.04 ± 0.02 mag dex $^{-1}$ with metal abundance. On the other hand, since the RR Lyraes in the LMC have period and amplitude distributions more similar to those of the M3 variables (see § 3.2), we can directly compare the observed average colors of the LMC RR Lyraes with those of the M3 ones. A further advantage of this choice is the very low reddening of M3, with $E(B-V)$ values in the range from 0.00 to 0.01 mag (Ferraro et al. 1997; Harris 1996; Schlegel et al. 1998; Cacciari et al. 2003).

Corwin & Carney (2001) have published accurate CCD B , V light curves for more than 200 RR Lyrae variables in M3. The magnitude-averaged $B-V$ color of the observed blue edge defined by Corwin et al. M3 RR Lyraes is 0.184 mag. This value compares extremely well with Walker (1998)'s dereddened color of the instability strip blue edge $(B-V)_0 = 0.18$, thus confirming the very low reddening suffered by M3. The M3 observed red edge is at $B-V = 0.402$ mag (Corwin & Carney 2001).

In Table 3 we list (intensity- and magnitude-averaged) $B-V$ colors for the five bluest and the five reddest LMC variables in the field A and B combined sample. Colors of the variables in field A have been made bluer by 0.03 mag to put them on the same reddening system of field B.

The first-overtone blue edge (FOBE) of the LMC RR Lyrae strip is very well defined by the three bluest stars in the left-hand portion of Table 3, namely, field B star 2517 and field A stars 2623 and 2223, giving an average color of the FOBE $\langle B-V \rangle_{FOBE} = 0.245$ ($\sigma = 0.011$).

The fundamental red edge (FRE) of the RR Lyrae instability strip is more difficult to define. Spectroscopic metal abundances are available for four of the five stars at the FRE, namely, stars 8094, 28293 in field A and stars 7468 and 5589 in field B. Colors were corrected to account for the difference in metallicity with M3 (assumed at [Fe/H] = –1.66 according to Zinn & West 1984) by applying the shift with metal abundance found by Walker (1998). Final adopted colors for the stars at the FRE are given in column (9) of Table 3. We used the three reddest stars in the right-hand portion of Table 3, namely, field A stars 8094, 28293, and 7468 in field B to obtain an average color of the FRE of $\langle B-V \rangle_{FRE} = 0.507$ ($\sigma = 0.023$).

Differences in color between the LMC and M3 FOBE and FRE are 0.061 and 0.105 mag, respectively. From the

TABLE 3
INSTABILITY STRIP EDGES DEFINED BY RR LYRAE VARIABLES IN OUR LMC FIELDS^a

FIRST OVERTONE BLUE EDGE				FUNDAMENTAL RED EDGE				
ID (1)	Field (2)	$\langle B \rangle - \langle V \rangle$ (int.) (3)	$\langle B \rangle - \langle V \rangle$ (mag) (4)	ID (5)	Field (6)	$\langle B \rangle - \langle V \rangle$ (int.) (7)	$\langle B \rangle - \langle V \rangle$ (mag) (8)	$\langle B \rangle - \langle V \rangle$ (adopted) (9)
2517.....	B	0.230	0.237	8094	A	0.509	0.517	0.525 ^b
2623.....	A	0.233	0.240	28293	A	0.502	0.508	0.514 ^b
2223.....	A	0.249	0.258	7468	A	0.481	0.489	0.481 ^b
4008.....	B	0.278	0.284	5589	A	0.475	0.480	0.480 ^b
7783.....	B	0.285	0.298	5452	A	0.473	0.473	0.473

^a Colors of the variables in field A have been made bluer by 0.03 mag to put them on the same reddening scale as field B.

^b Corrected colors derived using Walker 1998 0.04 mag dex $^{-1}$ shift of the color of the FRE with metal abundance and assuming [Fe/H] = –1.66 for M3 (Zinn & West 1984).

weighted average of these differences, with the FOBE having double weight, the reddening in field B should be 0.076 ± 0.016 larger than in M3 [i.e., larger than $E(B-V) = 0.010 \pm 0.007$ mag]. The reddening estimated from the colors of the RR Lyrae instability strip edges is then $E(B-V) = 0.086 \pm 0.017$ for field B, and $E(B-V) = 0.116 \pm 0.017$ for field A. These values agree well with the estimates obtained by Sturch's method if the 0.02–0.03 mag offset suggested by Walker (1998) is considered.

We verified that RR Lyraes in both field A and B, once corrected for the above reddening values, are very well confined within the edges of the instability strip defined by Corwin & Carney (2001) M3 variables, thus confirming the similarity of our LMC RR Lyrae sample to the OoI cluster M3, and giving support to the reddening values we determined in the two fields.

5. OUR RESULTS

5.1. Reddening and Luminosity

Hereafter we will adopt reddening values of $E(B-V) = 0.116 \pm 0.017$ and $E(B-V) = 0.086 \pm 0.017$ for field A and B, respectively. Reddening in field A is 0.028 mag smaller than derived by Udalski et al. (1999a) in the same area, and on average these new reddenings are 0.04 mag smaller than OGLE-II average reddening for the LMC [$E(B-V) = 0.143$, Udalski 2000b], and 0.03 mag smaller than estimated from the UBV photometry of early-type stars (Oestreicher et al. 1995; and Oestreicher & Schmidt-Kaler 1996). On the other hand, while reddening in field B within the quoted uncertainties agrees with the estimates based on Cepheids (0.067 ± 0.006), that in field A is clearly larger, and on average our values are 0.035 mag larger than reddenings derived from Cepheids. However, this result is not totally surprising since most of the Cepheids with measured reddening lie in regions far from the LMC bar and

none of them falls in our fields. We also note that, since we are using a large sample of ~ 100 objects projected into the direction of the bar, we also eliminated the possibility of systematic differences in the position of the barycenter, which is quite possible considering a small number of objects, such as, e.g., the globular clusters.

The absorption corrected intensity-averaged magnitudes of the total sample of RR Lyraes with full coverage of the light curves are $\langle V \rangle_0 = 19.053 \pm 0.021 \pm 0.053$ and $\langle B \rangle_0 = 19.329 \pm 0.023 \pm 0.070$; average values of each field were corrected for the corresponding reddening, adopting standard values for the selective absorption $R_V = 3.1$ mag, $R_B = 4.1$ mag (Cardelli et al. 1989). The first error bar is the internal dispersion of the average, while the second term is due to the 0.017 mag uncertainty in the reddening, still by far the largest uncertainty source. The final error should also include the contributions of the uncertainty of the photometric calibration and of the aperture corrections (0.017 mag in V and 0.032 mag in B , and 0.023 in V and 0.019 in B ; see DF03).

Adding up in quadrature all error contributions we derive for 108 objects: $\langle V \rangle_0 = 19.05 \pm 0.06$ and $\langle B \rangle_0 = 19.33 \pm 0.08$ for the average dereddened apparent luminosities of our sample of RR Lyrae stars in the bar of the LMC. A summary of our photometric results is provided in Table 4.

5.2. The Luminosity-Metallicity Relation

The absolute magnitude of the RR Lyraes, $M_V(\text{RR})$, is known to depend on metallicity $[\text{Fe}/\text{H}]$ according to the relation $M_V(\text{RR}) = \alpha \times [\text{Fe}/\text{H}] + \beta$, but rather large uncertainties exist both on the slope α and on the zero point β of this relation. The zero point has been already discussed (see § 1.1); we will now consider the slope.

The exact value of α has a large impact on several relevant astrophysical problems. For instance, when coupled with the almost constant value of $\Delta V_{\text{TO}}^{\text{HB}}$ found for globular

TABLE 4
SUMMARY OF OUR PHOTOMETRIC RESULTS^a

Field A	Field B
$\langle V(\text{RR}) \rangle = 19.412 \pm 0.019$	$\langle V(\text{RR}) \rangle = 19.320 \pm 0.023$
$\langle B(\text{RR}) \rangle = 19.807 \pm 0.022$	$\langle B(\text{RR}) \rangle = 19.680 \pm 0.024$
$\langle V(\text{clump}) \rangle = 19.304 \pm 0.002$	$\langle V(\text{clump}) \rangle = 19.291 \pm 0.003$
$\langle B(\text{clump}) \rangle = 20.215 \pm 0.003$	$\langle B(\text{clump}) \rangle = 20.194 \pm 0.003$
$\langle I(\text{clump}) \rangle = 18.319 \pm 0.002$	$\langle I(\text{clump}) \rangle = 18.307 \pm 0.003$
$E(B-V) = 0.116 \pm 0.017$	$E(B-V) = 0.086 \pm 0.017$
$R_V = 3.10$	$R_B = 4.10$
	$R_I = 1.94$
$\langle V(\text{RR}) \rangle_0 = 19.052$	$\langle V(\text{RR}) \rangle_0 = 19.053$
$\langle B(\text{RR}) \rangle_0 = 19.331$	$\langle B(\text{RR}) \rangle_0 = 19.327$
$\langle V(\text{clump}) \rangle_0 = 18.944$	$\langle V(\text{clump}) \rangle_0 = 19.024$
$\langle B(\text{clump}) \rangle_0 = 19.739$	$\langle B(\text{clump}) \rangle_0 = 19.841$
$\langle V(\text{clump}) \rangle_0 = 18.094$	$\langle V(\text{clump}) \rangle_0 = 18.140$
Average Values	
$\langle V(\text{RR}) \rangle_0 = 19.05 \pm 0.06$	
$\langle B(\text{RR}) \rangle_0 = 19.33 \pm 0.08$	
$\langle I(\text{clump}) \rangle_0 = 18.12 \pm 0.06$	

^a Errors in the lower portion of the table include internal dispersion of the average, contributions of the uncertainty of the photometric calibration and of the aperture corrections, and absorption contribution due to the uncertainty in the reddening.

clusters, the $M_V(\text{RR})$ -[Fe/H] relationship implies (1) that all clusters are more or less coeval if the high value of α is chosen or, conversely, (2) that there is a significant age-metallicity dependence in the family of the Galactic GCs (see Sandage 1993b and references therein) if a shallow slope is the correct value. The whole Galactic formation scenario is thus heavily affected by the precise knowledge of α .

RR Lyrae stars in the LMC bar may play a key role in the definition of α , since they can be considered all at the same distance from us, are very numerous, and span more than 1.5 dex range in metallicity. They can be used to firmly constrain the value of α , independently of any model assumption, the only limiting factor being the intrinsic spread in the luminosities of the RR Lyrae stars due to their evolution off the ZAHB. To minimize this effect a fairly large number of variables is needed.

We have combined the individual metal abundances of the RR Lyrae stars derived from our spectroscopic study with the corresponding dereddened mean apparent V luminosities and determined the slope of the luminosity-metallicity relation for RR Lyrae stars. We used 85 out of the 101 RR Lyrae stars we analyzed spectroscopically, i.e., those which have well-sampled V light curves and no shifts between 1999 and 2001 photometries. They were divided into five metallicities bins; for each bin we computed the average metal abundance, the average dereddened apparent luminosity V_0 , and their rms errors (see details in Gratton et al. 2003). A least-squares fit of these average values weighted by the errors in both variables gives the following relation for the apparent luminosity-metallicity relation of RR Lyrae stars:

$$\langle V_0(\text{RR}) \rangle = [0.214(\pm 0.047)] \\ \times ([\text{Fe}/\text{H}] + 1.5) + 19.064(\pm 0.017),$$

where the error in the slope was evaluated via Monte Carlo simulations.

This relation is shown in Figure 6, where open and filled symbols are used for single- and double-mode RR Lyrae stars, respectively. The mild slope we derive is in very good agreement with recent results based on the HB luminosity of 19 globular clusters in M31: $\Delta M_V(\text{RR})/\Delta[\text{Fe}/\text{H}] = 0.22$ mag dex $^{-1}$ (Rich et al. 2001) and it also agrees with the 0.20 ± 0.04 slope found by the Baade-Wesselink analysis of Milky Way field RR Lyrae stars: a confirmation that the same luminosity-metallicity relation for HB stars is valid in three different environments, namely, M31, the LMC, and

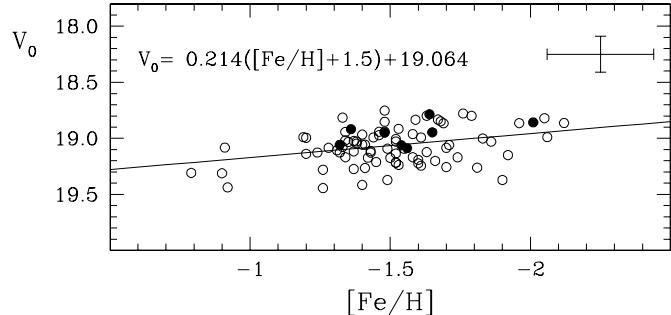


FIG. 6.—Luminosity-metallicity relation defined by our RR Lyrae stars. Filled circles mark the double-mode pulsators.

the Milky Way. Figure 6 does not show any clear evidence for the break in the slope around $[\text{Fe}/\text{H}] = -1.5$ suggested by recent evolutionary/pulsation and HB models.

Finally, we note that, in the V_0 -versus-[Fe/H] relation, the LMC RRd's are systematically offset to slightly higher luminosities, thus giving support to the hypothesis that the double-mode pulsators may be more evolved than their single-mode pulsator counterparts.

That RRd's might be more evolved than single-mode RR Lyrae stars has often been suggested on both observational and theoretical grounds; however, here for the first time we can test this hypothesis on a large sample of stars with known metal abundance and all at same distance from us.

6. COMPARISON WITH PREVIOUS PHOTOMETRIC RESULTS

6.1. The RR Lyrae Stars

The average absorption-corrected apparent V luminosity of the 108 RR Lyraes with full coverage of the light curve in our sample is $\langle V(\text{RR}) \rangle_0 = 19.06 \pm 0.02 \pm 0.03 \pm 0.05$, at an average metallicity of $[\text{Fe}/\text{H}] = -1.5 \pm 0.03$, on the Harris (1996) metallicity scale (see § 3.3 and Gratton et al. 2003), and for reddening values of 0.116 ± 0.017 and 0.086 ± 0.017 mag in field A and B, respectively (see § 4). Here 0.02 mag is the standard deviation of the average, 0.03 mag is the contribution due to uncertainties of photometric calibration and aperture corrections (0.017 and 0.023 mag, respectively), and 0.05 mag is the absorption contribution due to the 0.017 mag uncertainty in the reddening.

This value can be compared with the following estimates available in the literature: (1) $\langle V(\text{RR}) \rangle_0 = 18.95 \pm 0.04$, Walker (1992a; i.e., 19.04 ± 0.04 at $[\text{Fe}/\text{H}] = -1.5$), based on 182 variables in seven LMC globular clusters at $[\text{Fe}/\text{H}] = -1.9$ and for an average reddening value of $\langle E(B-V) \rangle = 0.09$ mag. The 0.04 mag error bar is the internal error, and Walker estimates that systematic errors due to photometric zero points and absorption are of the order of 0.02–0.03 and 0.05 mag, respectively; (2) $\langle V(\text{RR}) \rangle_0 = 19.14$, derived from A00 median value of 680 RRab's observed by the MACHO microlensing experiment, at $[\text{Fe}/\text{H}] = -1.6$ (i.e., 19.16 at $[\text{Fe}/\text{H}] = -1.5$) and for $E(B-V) = 0.1$ mag (Bessell 1991). A00 do not provide an evaluation of the error, and we have worked them out as follows: (a) we estimate a 0.073 mag photometric zero-point uncertainty, based on the combination of A99 (0.021 mag internal precision of the MACHO photometry) and A96 (± 0.07 mag mean error of a single point of the RR Lyrae photometry); and (b) 0.06 absorption uncertainty based on a 0.02 uncertainty in the reddening. Finally, the 0.09 mag total error is likely to be an underestimate, since it does not include the standard deviation of the average (not provided by A96 and A00). In this respect we note that A97 quotes 0.10 mag as a conservative estimate of the photometric uncertainties of MACHO photometry for the RR Lyrae stars; and (3) $\langle V(\text{RR}) \rangle_0 = 18.91 \pm 0.01$ mag at $[\text{Fe}/\text{H}] = -1.6$ (i.e., 18.93 at $[\text{Fe}/\text{H}] = -1.5$) and for an assumed reddening value of 0.143 mag, in Udalski (2000b).

In Table 5 we summarize the $\langle V(\text{RR}) \rangle_0$ values from the literature transformed to $[\text{Fe}/\text{H}] - 1.5$, and we also list the associated errors divided in internal contribution and systematic errors (photometric zero point and absorption components).

TABLE 5
COMPARISON WITH THE $\langle V(RR) \rangle_0$ -VALUES IN THE LITERATURE TRANSFORMED TO A COMMON VALUE OF [Fe/H] = -1.5

$\langle V(RR) \rangle_0$	N_{stars}	ERROR ^a					REFERENCE
		(1)	(2)	(3)	Total	REDDENING	
19.06	108	0.02	0.03	0.05	0.06	0.086–0.116	This paper
19.04	182	0.04	0.025	0.05	0.07	0.09	Walker 1992a
19.07 ^b	160	0.04	0.025	0.05	0.07	0.07	Walker 1992a
19.16 ^c	680	...	0.073 ^d	0.06 ^d	>0.09 ^d	0.1	A00–MACHO
18.92	71	...	0.015 ^e	0.08 ^e	>0.08	0.144 ^f	Udalski et al. 2000–OGLE-II LMC_SC21
18.93	0.01	0.015 ^e	0.08 ^e	0.08	0.143 ^g	Udalski 2000b–OGLE-II

^a (1) standard deviation of the average; (2) photometric zero point; (3) absorption contribution.

^b Average value without NGC 1841.

^c From A00 $V=19.45$ corrected for a reddening of $E(B-V) = 0.1$, as in A96, and for the metallicity.

^d These errors are our guess, according to the procedure described in § 6.

^e Sources for the photometric zero point and absorption contributions to the total error are Udalski et al. 1998 and Udalski 1998a, respectively.

^f Reddening is the average of the values for field LMC_SC21 in Table 2 of Udalski et al. 1999a. The 18.92 is obtained subtracting $3.1 \times 0.144 = 0.446$ mag from $\langle V(RR) \rangle = 19.37$ mag quoted in Udalski et al. 2000, and without metallicity correction since RR Lyraes in the OGLE-II field LMC_SC21 can be expected to share the same average metallicity as our field A.

^g Reddening is average of the values for all the LMC fields in Table 2 of Udalski et al. 1999a.

Summarizing,

1. The present average luminosity of the RR Lyrae stars in the LMC bar agrees well with Walker (1992a) photometry of RR Lyrae stars in the LMC globular clusters (both including or discarding NGC 1841), thus ruling out the existence of any intrinsic differences between field and cluster variables. Walker's and our V photometries are both on the same consistent Johnson photometric system, and we used both reddenings values measured with the very same procedure based on the intrinsic properties of the stars whose average luminosities are compared.

2. Our $\langle V(RR) \rangle_0$ is about 0.1 mag brighter than the MACHO A00 value, contrary to A99, who found a systematic negative shift of $\Delta V = -0.035$ between MACHO and other photometric works, implying higher luminosities for MACHO. As discussed in § 2.2 and DF03, this difference is almost entirely due to the difference existing between MACHO and our photometry for field A, the results for field B being in agreement with ours. On the other hand, the average luminosity of the RRd stars in our sample, $\langle V \rangle = 19.331 \pm 0.055$ ($\sigma = 0.175$, 10 stars), is in excellent agreement with A00's recalibration of A97 luminosity of the LMC RRd's ($\langle V \rangle = 19.327 \pm 0.021$).

3. In Table 5 the two values listed for OGLE correspond to the average luminosity of the total sample of RR Lyrae stars (Udalski 2000b) and to the luminosity of the subsample of RR Lyrae stars in OGLE field LMC_SC21 with declination within the limits of our Field A (Udalsky et al. 2000). Both OGLE values are systematically brighter by 0.14, 0.24, and 0.15 mag (or 0.12 mag if NGC 1841 is included) than the present photometry, A00, and Walker (1992a), respectively. The total error bar of Udalski et al.'s (2000) determination only marginally allows to make their $\langle V(RR) \rangle_0$ values overlap with the estimate from the present photometry. The offset between OGLE-II and our average luminosity for the RR Lyrae stars is due for about 0.06 mag to the zero-point shift existing between the two photometries (caused by an overestimate of star brightness at the faint limit of OGLE-II photometry, likely due to the different data reduction packages; see DF03) and for the remaining 0.08 mag to OGLE-II overestimate by about 0.02–0.03 mag of the reddening in these areas of the LMC.

Using the average absolute magnitudes for RR Lyrae stars considered in § 1.1 ($M_V = 0.72 \pm 0.15$ at [Fe/H] = -1.5, average of the values from statistical parallaxes and the B-W method), we obtain a distance modulus of $\mu_{\text{LMC}} = 18.34 \pm 0.15$. If we instead adopt the value recently obtained from the globular cluster main-sequence fitting by Gratton et al. (2002, $M_V = 0.61 \pm 0.07$ at [Fe/H] = -1.5), we obtain a slightly longer distance modulus of $\mu_{\text{LMC}} = 18.45 \pm 0.09$.

6.2. The Clump

We present here results on the clump, since it is relevant for the distance to the LMC. In fact, the I_0 luminosity of the clump stars by the OGLE team gives the shortest distance modulus to the LMC. Udalski et al.'s (1998) modulus of 18.08 ± 0.15 mag has undergone a number of revisions which have moved it toward longer values (18.18 ± 0.06 , Udalski 1998b; 18.24 ± 0.08 , Udalski 2000a), but even the Popowski (2000) latest increase to 18.27 ± 0.07 still provides the shortest modulus derived so far for the LMC. Somewhat short distance moduli were also provided by two LMC eclipsing binary systems (namely, HV 2274, Guinan et al. 1998, and HV 982, Fitzpatrick et al. 2000); however, Ribas et al. (2002), in their recent analysis of a third LMC binary system (EROS 1044), conclude that the three binaries provide a consistent distance modulus to the barycenter of the LMC of 18.4 ± 0.1 .

A lively discussion is in progress among scientists over whether the clump method is reliable or not, and invoking (or not) metallicity and age effects and dependences of the absolute luminosity of the clump at various different extent (see, e.g., Girardi & Salaris 2001 and references therein). A much longer clump distance to the LMC has been published by Romaniello et al. (2000) based on *HST* WFC2 observations of a field around SN1987A: $\mu_{\text{LMC}} = 18.59 \pm 0.04 \pm 0.08$. More recent applications of this technique make use of the K-band luminosity of the LMC red clump stars (Sarajedini et al. 2002; Pietrzyński & Gieren 2002). The derived distance moduli are: $\mu_{\text{LMC}} = 18.54 \pm 0.10$ and $\mu_{\text{LMC}} = 18.59 \pm 0.008 \pm 0.048$, respectively, and Pietrzyński & Gieren (2002) emphasize

that, due to uncertainties on population corrections, actual errors of the clump method are as large as 0.12 mag.

Hipparcos measured parallaxes for clump stars in the solar neighborhood and derived for them an absolute V magnitude of about +0.8 mag, with a width of about 0.7 mag (FWHM, Jimenez, Flynn, & Kotoneva 1998), and a $B-V$ color of about 1.1 mag, with a range of about $0.86 \lesssim B-V \lesssim 1.34$ mag (read from Fig. 4 of Jimenez et al.). This is 0.1 mag *fainter* than the absolute V magnitude of RR Lyrae stars at $[Fe/H] = -1.5$, the typical value for the LMC variables, if the absolute magnitude given by the statistical parallaxes and the B-W method is adopted.

A00 found that the red HB clump of the 9M CMD is 0.28 mag *brighter* than the mean brightness of the RR Lyrae stars. This difference is larger than predicted by theory for an old, coeval HB population, thus leading to the conclu-

sion that RR Lyrae and clump stars in the LMC have different ages.

We may directly compare the mean apparent V magnitudes of the RR Lyrae and clump stars in our LMC fields. This comparison is shown in Figure 7, where we plot enlargements of the RR Lyrae and HB red clump region in the HR diagrams of our fields. In each panel of the figure, the boxes outline the clump stars of the field, chosen to lie in the region $B-V = 0.65-1.20$, and $V = 19.70-18.9$ in Field A, and $B-V = 0.62-1.17$ and $V=19.61-18.81$ in field B, and containing 6728 and 3851 stars, respectively. Gaussian fittings of the B , V , and I luminosity functions provide the following average magnitudes and colors of the clump: $\langle B \rangle = 20.215$ mag, $\sigma = 0.207$, $\langle V \rangle = 19.304$ mag, $\sigma = 0.185$, $\langle I \rangle = 18.319$ mag, $\sigma = 0.190$, $\langle B \rangle - \langle V \rangle = 0.911$ mag, and $\langle V \rangle - \langle I \rangle = 0.985$ mag in field A; and $\langle B \rangle = 20.194$ mag, $\sigma = 0.202$, $\langle V \rangle = 19.291$ mag, $\sigma = 0.188$, $\langle I \rangle = 18.307$

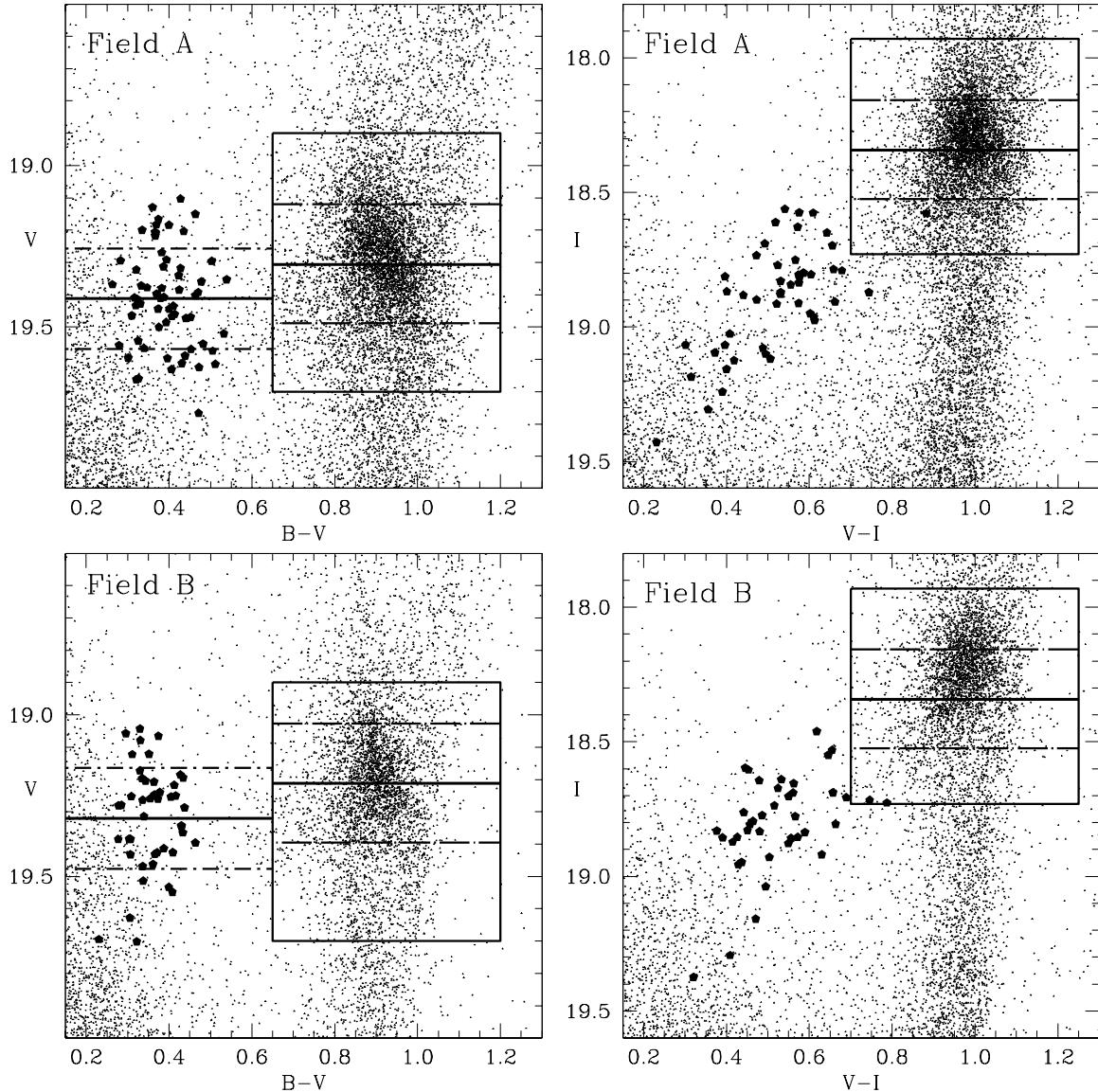


Fig. 7.—Enlargement of the regions containing the RR Lyrae and clump stars in the V vs. $B-V$, and I vs. $V-I$ CMDs of field A (top) and B (bottom), respectively. Filled pentagons are the RR Lyrae plotted according to their intensity-averaged magnitudes and colors. Solid lines in the left-hand panels indicate the average levels of the RR Lyrae ($\langle V(RR)_A \rangle = 19.412$ mag, $\langle V(RR)_B \rangle = 19.320$ mag), and clump stars ($\langle V_{Clump_A} \rangle = 19.304$ mag, $\langle V_{Clump_B} \rangle = 19.291$ mag) in each field. Dot-dashed lines represent the 1σ deviations from the averages (~ 0.16 and ~ 0.19 mag for RR Lyrae and clumps stars, respectively).

mag, $\sigma = 0.184$, $\langle B \rangle - \langle V \rangle = 0.903$ mag, and $\langle V \rangle - \langle I \rangle = 0.984$ mag in field B. These values can be compared with $\langle I_{\text{clump}} \rangle = 18.25$ reported by OGLE-II (from $\langle I_0 \rangle = 17.97$ by Udalski 2000b, with $E(B-V) = 0.143$, and $A_I = 1.96E(B-V)$ from Udalski et al. 1999a). A summary of our photometric results for the clump is provided in Table 5.

Clearly the LMC red clump has a complex structure resulting from the superposition of stellar populations with different masses and ages. Evolutionary and age effects are then present and should be properly accounted for when the HB red clump is used as a distance indicator. On the other hand, the contribution to the clump by the old horizontal branch in the LMC is very well defined by its RR Lyrae stars. Figure 7 shows that the average luminosity of RR Lyrae stars corresponds to the lowest envelope of the clump. In fact, the average V apparent luminosity of the clump stars is 0.108 and 0.029 mag *brighter* than the RR Lyrae level in field A and B, respectively. These results show that (1) the properties of the clump population in field A and B are different, and a population gradient is likely to exist between the two areas; (2) the properties of the clump population are quite different in the LMC and in the solar neighborhood. This is not unexpected. However, the differences in M_V are not those expected based on OGLE-II results.

The fine structure of the red HB clump stars in our LMC fields will be investigated more in detail in a following paper with the help of the metallicity distribution drawn from about 300 clump stars we observed spectroscopically. Here we only outline the effects on the clump distance modulus to the LMC due to our new estimate for I_0 .

According to our reddening estimates in the two fields and adopting the Schlegel et al. (1998) value for the absorption in the I band, $A_I = 1.94E(B-V)$, the dereddened average luminosity of the clump is $I_0 = 18.12 \pm 0.06$ mag (where the error bar includes standard deviation of the average, photometric zero point, and absorption contribution). This value is in excellent agreement with Romanielo et al. (2000) but is 0.15 mag *fainter* than in Udalski (2000b). This difference is accounted for by the 0.07 mag offset existing between our and OGLE-II photometries at the luminosity level of the clump (see § 2.2 and DF03), and by a 0.08 mag difference in the I -band absorption, with OGLE-II reddening being about 0.04 mag larger than our average reddening (see §§ 4 and 5.1).

Using the metallicity- I luminosity calibration for the clump stars by Udalski [2000a; $M_I = 0.13([\text{Fe}/\text{H}] + 0.25) - 0.26$], and assuming a mean metallicity of $[\text{Fe}/\text{H}] = -0.55$ (again as in Udalski 2000a), we find a distance modulus of $(m - M)_{0,\text{LMC}} = 18.42 \pm 0.07$; while, if we adopt instead the calibration by Popowski (2000, $M_I = 0.19[\text{Fe}/\text{H}] - 0.23$), we obtain $(m - M)_{0,\text{LMC}} = 18.45 \pm 0.07$. These values are larger than those found by Udalski (2000a, 2000b) and Popowski (2000), and in agreement with almost all other distance modulus determinations for the LMC (see Fig. 7). Lacking at present precise estimates of the metallicities of the clump stars in our fields, these values have to be considered as preliminary. However, given the low sensitivity of M_I on metallicity, the assumption about the metal abundance of the clump stars has little impact on this distance derivation.

7. SUMMARY AND CONCLUSIONS: THE DISTANCE TO THE LMC

We have presented results based on new B , V , I photometry in the Johnson-Cousins system obtained for two fields

close to the bar of the LMC and partially overlapping with fields 6 and 13 of the MACHO microlensing experiment. 125 RR Lyrae variables, three anomalous Cepheids, 11 Cepheids, 11 eclipsing binaries, and one δ Scuti star have been identified in the two areas. The new photometry allows a very precise estimate of the average V and B apparent luminosity of the RR Lyrae variables, as well as of the V , B , I luminosity of the clump stars. The present new photometry has been accurately compared with MACHO and OGLE-II photometries. An estimate of the reddening within the two fields was also obtained from Sturch's (1966) method and from the colors of the edges of the instability strip defined by the RR Lyrae variables. This corresponds to $E(B-V) = 0.116$, and 0.086 mag in field A and B, respectively. These values are on average about 0.03–0.04 mag smaller than reddening derived from the UBV photometry of early-type stars, and by OGLE-II, and about 0.035 mag larger than reddening estimated from Cepheids within 2° from either of the centers of our fields.

Spectroscopic metal abundances we derived for 80% of the RR Lyrae stars were combined with individual dereddened average luminosities to determine the luminosity-metallicity relation followed by the RR Lyrae stars: $\langle V_0(\text{RR}) \rangle = 0.214([\text{Fe}/\text{H}] + 1.5) + 19.064$. The slope of this relation is in very good agreement with recent results from GCs in M31 (Rich et al. 2001) and shows no evidence for a break around $[\text{Fe}/\text{H}] = -1.5$.

The average dereddened apparent luminosity of the RR Lyrae and clump stars in our LMC fields is $\langle V(\text{RR}) \rangle = 19.06 \pm 0.06$ (at $[\text{Fe}/\text{H}] = -1.5$), and $\langle V_{\text{clump}} \rangle_0 = 18.98 \pm 0.08$, where errors include standard deviation of the average (0.02 and 0.06 mag for RR Lyrae and clump stars, respectively), uncertainty of the V photometric calibration and aperture corrections, and absorption contribution.

The present $\langle V(\text{RR}) \rangle_0$ moves the B-W and statistical parallax determinations of the distance modulus of the LMC to 18.38 ± 0.16^{14} and 18.30 ± 0.14 , respectively. Using the most recent results from the subdwarf fitting method (Gratton et al. 2002), it is 18.45 ± 0.09 .

The present determination of the I luminosity of the clump stars corrected for our new reddening values leads to $\langle I \rangle_0 = 18.12 \pm 0.06$ mag and moves the clump distance modulus of the LMC to 18.42 ± 0.07 and 18.45 ± 0.07 mag, when Udalski's (2000a) or Popowski's (2000) metallicity- I luminosity relations for the clump stars are adopted.

The state-of-the-art on the true distance modulus of the LMC as derived from various techniques is summarized in Figure 8, where different symbols are adopted for Population I (*triangles*) and II (*circles*) distance indicators. Far from pretending to be exhaustive (see Fig. 8 and Table 10 of Benedict et al. 2002, for a more extensive listing of extant LMC distance modulus estimates), Figure 8 is meant to provide an overview of the results from the most commonly used and more robust distance indicators found in the LMC. In Figure 8a distance moduli from Population II indicators are based on Walker (1992a) average luminosity of RR Lyraes in the LMC Globular clusters: $\langle V(\text{RR}) \rangle_0 = 18.95$ at $[\text{Fe}/\text{H}] = -1.9$ (transformed to $[\text{Fe}/\text{H}] = -1.5$). Figure 8a well

¹⁴ The B-W value would further move to 18.50 mag using the new preliminary estimate of the magnitude of the Galactic field RR Lyrae star RR Cet: $M_V(\text{RR}) = 0.56$ mag at $[\text{Fe}/\text{H}] = -1.5$, from Cacciari et al. (2000) revision of the B-W method.

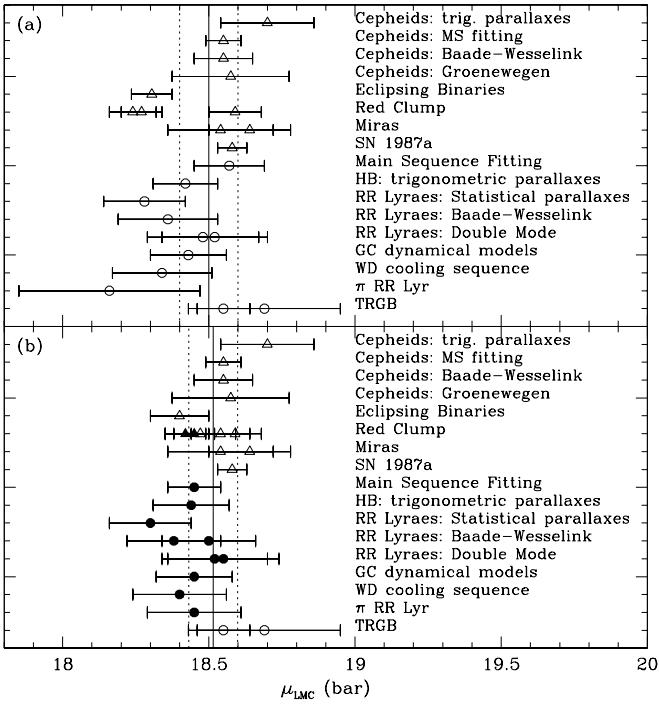


FIG. 8.—Distance modulus of the Large Magellanic Cloud as derived from various distance indicators. Triangles and circles mark the Population I and II indicators, respectively. (a) Distance moduli from Population II indicators are based on Walker (1992a) average luminosity of RR Lyrae in the LMC Globular clusters: $\langle V(\text{RR}) \rangle_0 = 18.95$ at $[\text{Fe}/\text{H}] = -1.9$ (transformed to $[\text{Fe}/\text{H}] = -1.5$); while in (b) distance moduli are based on our new average luminosities of RR Lyrae and clump stars in the bar of the LMC: $\langle V(\text{RR}) \rangle_0 = 19.06$ at $[\text{Fe}/\text{H}] = -1.5$, and $\langle I_{\text{Clump}} \rangle_0 = 18.12$, and on our new reddening estimates: $E(B-V) = 0.116$ and 0.086 mag (in field A and B, respectively). The solid and dashed lines in (a) shows the *HST* key project on extragalactic distances preferred value $\mu_{\text{LMC}} = 18.50$ and its $1\sigma = 0.10$ mag error bar (see Freedman et al. 2001 and § 7). Data in (a) of the figure for the Cepheids are taken from: trigonometric parallaxes, Feast & Catchpole (1997; with error bar revised according to Carretta et al. 2000b); MS fitting, Laney & Stobie (1994 value corrected to account for *Hipparcos* new distance modulus for the Hyades, and with error bar revised according to Carretta et al. 2000b); B-W, average of Gieren et al. (1998) value corrected according to Carretta et al. (2000b), and of Di Benedetto (1997) estimate; P/L relation from Groenewegen (2000); for the eclipsing binaries: average from Guinan et al. (1998) and Fitzpatrick et al. (2000); for the clump from: Udalski (2000a), Popowski (2000), and Romaniello et al. (2000); for the Miras from: Van Leeuwen et al. (1997) and Feast (2000); for SN 1987a from: Panagia (1998); for the MSF and the HB stars from: Carretta et al. (2000b); for the RR Lyrae Statistical parallaxes and B-W: from $M_V(\text{RR}) = 0.76$ and 0.68 mag, respectively, and Walker (1992a) $\langle V(\text{RR}) \rangle_0$; for the LMC RRD's from A97 and from Kovács (2000); for the GCs dynamical models from: Carretta et al. (2000b) revision of Chaboyer et al. (1998); for the white dwarfs cooling sequence from: Carretta et al. (2000b); for the *Hipparcos* trigonometric parallax of RR Lyrae itself: Perryman et al. (1997); and for the RGB tip Cioni et al. (2000), and Romaniello et al. (2000). The revision of the LMC distance moduli due to the present new photometry and reddening is shown in (b). Further changes with respect to (a) are: (1) Ribas et al. (2002) revised estimate of the distance to the LMC from the three eclipsing binary systems HV 2274, HV 982, and EROS 1044; (2) the clump distances based on the K-luminosity (Sarajedini et al. 2002, and Pietrzyński & Gieren 2002); (3) the revised MSF distances to GCs by Gratton et al. (2002); (4) Cacciari et al. (2000) revised estimate of $M_V(\text{RR})$ from the B-W method; (5) A00 revised average luminosity of A97 LMC RRD's; (6) the revised distance from the WD cooling sequence by Gratton et al. (2002); and (7) Benedict et al. (2002) trigonometric parallax of RR Lyr measured by *HST*. The solid line shows the average value of all distance moduli in (b): $\mu_{\text{LMC}} = 18.515$ mag, while dashed lines give the $1\sigma = 0.085$ mag error bars (see § 7).

illustrates the dichotomy existing between *short* and *long* distance scales provided by the different distance indicators: with a few exceptions (the red clump and the eclipsing binaries method), the Population I distance indicators give a *long* distance modulus for the LMC in the range from 18.5 to 18.7 mag, while Population II indicators based on “field stars” (Baade-Wesselink and statistical parallax methods, in particular) yield a *short* distance modulus of 18.3, and indicators based on “cluster stars,” as for instance the main-sequence fitting method (MSF; Gratton et al. 1997; Carretta et al. 2000b) and the globular clusters dynamical models, or the pulsational properties of RR Lyrae in globular clusters (Sandage 1993a) support a *longer* modulus in the range from 18.4 to 18.6. The solid and dashed lines in Figure 8a shows the *HST* key project on extragalactic distances preferred value $\mu_{\text{LMC}} = 18.50$ and its $1\sigma = 0.10$ mag error bar (Freedman et al. 2001).

The impact on the derived distance modulus of the LMC of the present average luminosities of RR Lyrae and clump stars in the LMC bar: $\langle V(\text{RR}) \rangle_0 = 19.06$ at $[\text{Fe}/\text{H}] = -1.5$, and $\langle I_{\text{Clump}} \rangle_0 = 18.12$, and of our new reddening estimates: $E(B-V) = 0.116$ and 0.086 mag (in field A and B, respectively) is shown in Figure 8b. Further changes with respect to Figure 8a are (1) the revised estimate of the distance to the LMC from the combinations of the results for three LMC binary systems studied so far (namely, HV 2274, HV 982 and EROS 1044; Ribas et al. 2002); (2) the clump distance based on K-luminosity (Sarajedini et al. 2002; Pietrzyński & Gieren 2002); (3) the revised HB luminosity from the new main-sequence-fitting (MSF) distances to NGC 6397, NGC 6752, and 47 Tuc, based on ESO-VLT spectroscopy of cluster giants and turnoff stars (Gratton et al. 2002); (4) Cacciari et al. (2000) revised estimate of $M_V(\text{RR})$ from the Baade-Wesselink method; (5) the use of A00’s revised average luminosity of A97 LMC RRD’s; (6) the revision of the absolute luminosity of RR Lyrae stars from the white dwarf (WD) cooling sequence: $M_V(\text{RR}) = 0.66 \pm 0.14$ at $[\text{Fe}/\text{H}] = -1.5$ (Gratton et al. 2002); and (7) the use of the trigonometric parallax of RR Lyr measured by *HST* (Benedict et al. 2002). Distance moduli shown in Figure 8b are also listed in Table 6. Errors for the Population II indicators in Figure 8b and Table 6 include the 0.06 mag contribution of the uncertainty in $\langle V(\text{RR}) \rangle_0$.

A weighted average of the values in Table 6 (with weights proportional to the inverse square of the error and after having first weight-averaged the independent estimates available for the clump, the Miras, the B-W of RR Lyrae stars, the RRD’s, and the TRGB) shows that *all* distance determinations converge within 1σ on a distance modulus of $\mu_{\text{LMC}} = 18.515 \pm 0.085$ mag (where the error bar is the 1σ scatter of the average) thus allowing to *fully reconcile the long and the short distance scale to the LMC*. This value is shown by the solid line of Figure 8b, while the dashed lines give the $1\sigma = 0.085$ mag error bars. A straight average of the values in Table 6, with no weights, would give $\mu_{\text{LMC}} = 18.50 \pm 0.10$. We caution that distance moduli from Cepheids may be overestimated by 0.06–0.09 mag because of an underestimate of the reddening adopted for Cepheids by 0.02–0.03 mag.

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TABLE 6
DISTANCE MODULI TO THE LMC FROM POPULATION I AND II DISTANCE INDICATORS

Method	μ_{LMC}	References
Population I Distance Indicators		
Cepheids: trig. paral.	18.70 ± 0.16 ^a	Feast & Catchpole 1997
Cepheids: MS fitting.....	18.55 ± 0.06 ^b	Laney & Stobie 1994
Cepheids: B-W	18.55 ± 0.10 ^c	Gieren et al. 1998, Di Benedetto 1997
Cepheids: P/L relation	18.575 ± 0.2	Groenewegen 2000
Eclipsing binaries.....	18.4 ± 0.1	Ribas et al. 2002
Clump.....	18.42 ± 0.07	This paper; see § 6.2
Clump.....	18.45 ± 0.07	This paper; see § 6.2
Clump.....	18.59 ± 0.09	Romanillo et al. 2000
Clump.....	18.471 ± 0.12	Pietrzynsky & Gieren 2002
Clump.....	18.54 ± 0.10	Sarajedini et al. 2002
Miras	18.54 ± 0.18	Van Leeuwen 1997
Miras	18.64 ± 0.14	Feast 2000
SN 1987a	18.58 ± 0.05	Panagia 1998
Population II Distance Indicators		
GCs: MSF	18.45 ± 0.09	Gratton et al. 2002 and this paper
GCs: dyn. mod.....	18.45 ± 0.13	Carretta et al. 2000b and this paper
HB: trig. paral.	18.44 ± 0.13	Carretta et al. 2000b and this paper
RR Lyr: stat. paral.	18.30 ± 0.14	This paper; see § 7
RR Lyr: BW	18.38 ± 0.16	This paper; see § 7
RR Lyr: BW revised.....	18.50 ± 0.16	Cacciari et al. 2000 and this paper
LMC RRd's.....	18.55 ± 0.19	A97 and A00
LMC RRd's.....	18.52 ± 0.18	Kovács 2000 and this paper
WD cool. seq.....	18.40 ± 0.15	Gratton et al. 2002 and this paper
RRLyr: trig. par.....	18.45 ± 0.16	Benedict et al. 2002 and this paper
TRGB.....	18.55 ± 0.09	Cioni et al. 2000
TRGB.....	18.69 ± 0.26	Romanillo et al. 2000.

^a Error bar has been revised according to Carretta et al. 2000b.

^b Laney & Stobie 1994 original value corrected to account for *Hipparcos* new distance modulus for the Hyades; see Carretta et al. 2000b.

^c Average of Gieren et al. 1998 value, corrected according to Carretta et al. 2000b, and of Di Benedetto 1997 estimate.

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