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THE ARAUCARIA PROJECT: DEEP NEAR-INFRARED SURVEY OF NEARBY GALAXIES. I. THE DISTANCE TO THE LARGE MAGELLANIC CLOUD FROM *K*-BAND PHOTOMETRY OF RED CLUMP STARS[1]

G. Pietrzyński
Departamento de Física, Universidad de Concepción, Casilla 160-C, Concepción, Chile;
and Warsaw University Observatory, Aleje Ujazdowskie 4, 00-478 Warszawa, Poland;
pietrzyn@hubble.cfm.udec.cl

and

W. Gieren
Departamento de Física, Universidad de Concepción, Casilla 160-C, Concepción, Chile;
wgieren@coma.cfm.udec.cl
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ABSTRACT

We have obtained deep imaging in the near-infrared *J* and *K* bands for two nearby fields in the bar of the LMC with the ESO New Technology Telescope, under exquisite seeing conditions. The *K*, $J-K$ color-magnitude diagrams constructed from these data are of outstanding photometric quality and reveal the presence of several hundred red clump stars. Using the calibration of Alves for the *K*-band absolute magnitude of *Hipparcos*-observed red clump stars in the solar neighborhood, we derive a distance modulus to our observed LMC fields of 18.487 mag. Applying a correction for the tilt of the LMC bar with respect to the line of sight according to the geometrical model of van der Marel et al., the corresponding LMC barycenter distance is 18.501 mag. The random error on this result is ± 0.008 mag, whereas the systematic uncertainty on this distance result due to the photometric zero-point uncertainty in our LMC *K*-band photometry, to the uncertainty of the *Hipparcos*-based absolute magnitude calibration of red clump stars in the solar neighborhood, and to reddening uncertainties mounts up to ± 0.048 mag. If we adopt a *K*-band population correction of -0.03 mag, as done by Alves et al., to account for the difference in age and metallicity between the solar neighborhood and LMC red clump star populations, we obtain an LMC barycenter distance modulus of 18.471 mag from our data. This is in excellent agreement with the results of Alves et al. and those of another very recent study by Sarajedini et al. obtained from *K*-band photometry. However, we emphasize that current model predictions about the uncertainties of population corrections seem to indicate that errors up to about 0.12 mag may be possible, probably in any photometric band. Therefore, work must continue to tighten the constraints on these corrections. We also determine the mean red clump star magnitude in our LMC fields in the *J* band, which could be a useful alternative to the *K* band should future work reveal that population effect corrections for red clump stars in the *J* band are smaller or more reliably determined than those for the *K* band.

Key words: distance scale — galaxies: distances and redshifts — galaxies: individual (Large Magellanic Cloud)

1. INTRODUCTION

We have recently started on an ambitious project to improve the calibrations of a number of stellar distance indicators that can be used to determine the distances to nearby galaxies, located at $\lesssim 10$ Mpc. This project, named the Araucaria Project, is particularly focusing on the dependence of the various stellar distance indicators on galaxy environmental properties, such as metallicity and age of the stellar populations. Among the objects whose usefulness for an accurate distance measurement we want to improve within the Araucaria Project are Cepheid variables, RR Lyrae stars, red clump stars, blue supergiants, and planetary nebulae. These stellar distance indicators span a large range in mass, typical age, and evolutionary state, and in any galaxy at least some of these object classes can be found. In the Local Group and other nearby galaxy groups such as Sculptor, there are a number of galaxies that contain stellar populations of all ages (old, intermediate, and young) and in which all of our standard candles can be found together—these are our principal target galaxies for establishing the possible environmental dependences of our stellar standard candles more accurately than hitherto done. The aims of the project have been described in more detail in Gieren et al. (2001), and first results have recently been published in Pietrzyński et al. (2002a).

As a part of the Araucaria Project, we are conducting a deep near-infrared (*JK*) imaging survey in several of our target galaxies, including the Magellanic Clouds and the Carina and Fornax dwarf galaxies. An immediate aim is to use red clump stars and the tip of the red giant branch technique to determine the distances to these galaxies. In this paper, we are presenting a distance determination to the Large Magellanic Cloud from the red clump star method, applied in the pure infrared domain (from a *K*, $J-K$ color-magnitude diagram). The LMC is arguably the most important galaxy in the process of establishing an accurate extragalactic distance scale, and our current lack of ability

[1] Based on observations obtained with the New Technology Telescope at the European Southern Observatory as part of project 69.D-0352.

to measure extragalactic distances is best reflected in the large range of distances measured for the LMC with different techniques (e.g., Gibson 2000). Regarding the red clump stars as a distance indicator, the method was introduced in a fundamental paper of Paczyński & Stanek (1998), and the red clump star mean brightness was calibrated in the optical V and I bands in their paper. Important progress has recently been made by Alves (2000), who was the first to calibrate the absolute magnitudes of a large sample of *Hipparcos*-observed nearby red clump stars in the K band. An outstanding and obvious advantage of the red clump star technique is the fact that accurate distances were measured by *Hipparcos* to nearly a thousand of these stars in the solar neighborhood, making the red clump star method currently the only technique having a zero point that is set from an accurate geometrical calibration (Paczyński & Stanek 1998). While previous efforts to calibrate the red clump star absolute magnitude in the optical I band and apply it to other galaxies were plagued by problems with extinction corrections and with a small but significant dependence of M_I on metallicity, which manifested themselves in considerable differences between red clump distances to the LMC using I-band magnitudes (e.g., Udalski et al. 1998, 2000; Romaniello et al. 2000), the use of K-band magnitudes minimizes these problems and, in the case of the LMC, virtually eliminates any dependence of the final K-band red clump distance result on the adopted reddening. In the very recent work of Grocholski & Sarajedini (2002), who studied population effects on the K-band magnitude of red clump stars from Two Micron All Sky Survey (2MASS) photometry of open clusters, it was suggested that M_K may be less dependent on stellar age and metallicity than M_I. Therefore, it is of profound importance to verify in detail possible population effects on the mean K-band red clump magnitude in order to be able to derive truly accurate distances with this method.

In the following, we describe what we believe is the as yet most accurate set of near-IR data for samples of red clump stars in two fields in the bar of the LMC, obtained with the New Technology Telescope (NTT) on La Silla under superb seeing conditions, analyze these data together with optical photometry of the red clump stars in these fields taken from Optical Gravitational Lensing Experiment (OGLE) II databases, and derive the distance to the LMC. We thoroughly discuss the accuracy of our distance determination, including the effect of environmental corrections on our (and other) results. In forthcoming papers, we will extend this work to a number of galaxies in the Local Group, in an effort to tighten the constraints on the appropriate corrections that have to be applied to the observed red clump star magnitudes to account for differences in the red clump star populations that we are observing in these galaxies and in the solar neighborhood.

2. OBSERVATIONS

All observations presented in this paper were collected with the ESO/NTT telescope at the La Silla observatory in Chile. The SOFI instrument in wide-field mode with a focal elongator in the grism wheel was used. The resulting field of view was about 2ʹ.49 × 2ʹ.49 with a scale of 0ʺ.146 pixel^{-1}. This configuration guaranteed an excellent image quality (superior to the quality achievable in other SOFI modes) with a very stable point-spread function (PSF) over the whole CCD, which was a substantial advantage in deriving accurate PSF photometry in the dense fields of the LMC bar.

TABLE 1
Observed Fields

Field	R.A. (J2000.0)	Decl. (J2000.0)	N Stars	N_{RC}
FI..........	05 33 39.5	−70 09 36.5	1472	464
FII	05 33 53.8	−70 04 01.9	1441	494

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

Two fields (see Table 1) were observed through K_s and J filters, under photometric and 0ʺ.6 seeing conditions. In order to account for frequent sky-level variations, especially in the K band, the observations were made with a jittering technique. In the K_s filter, we did six consecutive 10 s integrations in any given sky position before moving the telescope by about 20ʺ to a different position. We used 20 different jittering positions in K_s, which resulted in a total net exposure time of about 20 minutes in the K_s filter. The J-band data were obtained in a similar fashion, but for each telescope jittering position we obtained only one 10 s integration, leading to a total integration time of about 3 minutes in this filter. In order to accurately transform our data to the standard system, we secured nine observations of seven different standard stars from the United Kingdom Infrared Telescope (UKIRT) system (Hawarden et al. 2001) at a variety of air masses and spanning a broad range in color, bracketing the red clump star colors, along with our LMC fields.

3. REDUCTIONS AND CALIBRATIONS

Sky subtraction of the images was performed in a two-step process implying masking of stars with the *xdimsum* IRAF package. As a next step, the data were flat-fielded and stacked into the final images. The PSF photometry was derived with the DAOPHOT and ALLSTAR programs. The PSF model was obtained in an iterative way that was described in detail in Pietrzyński, Gieren, & Udalski (2002b). In order to derive aperture corrections, about 50 relatively isolated stars were selected on each image. Then all stars located in the neighborhood of those stars were iteratively subtracted, and aperture photometry on the selected stars was carried out. The median from the aperture corrections derived for all selected isolated stars was adopted as the final aperture correction for a given frame. The typical rms scatter of the aperture corrections derived in this way was about 0.008 mag.

Aperture photometry on the standard stars was performed by choosing an aperture of 14 pixels. From our instrumental magnitudes, the following transformations to the standard system were derived:

$$J - K = 0.930(j - k) + 0.620 ,$$

$$K = k - 0.036(j - k) - 2.704 ,$$

where $J-K$ and K stand for the standard color and magnitude in the UKIRT system and $j-k$ and k denote the instrumental aperture magnitudes scaled to 1 s exposure times.

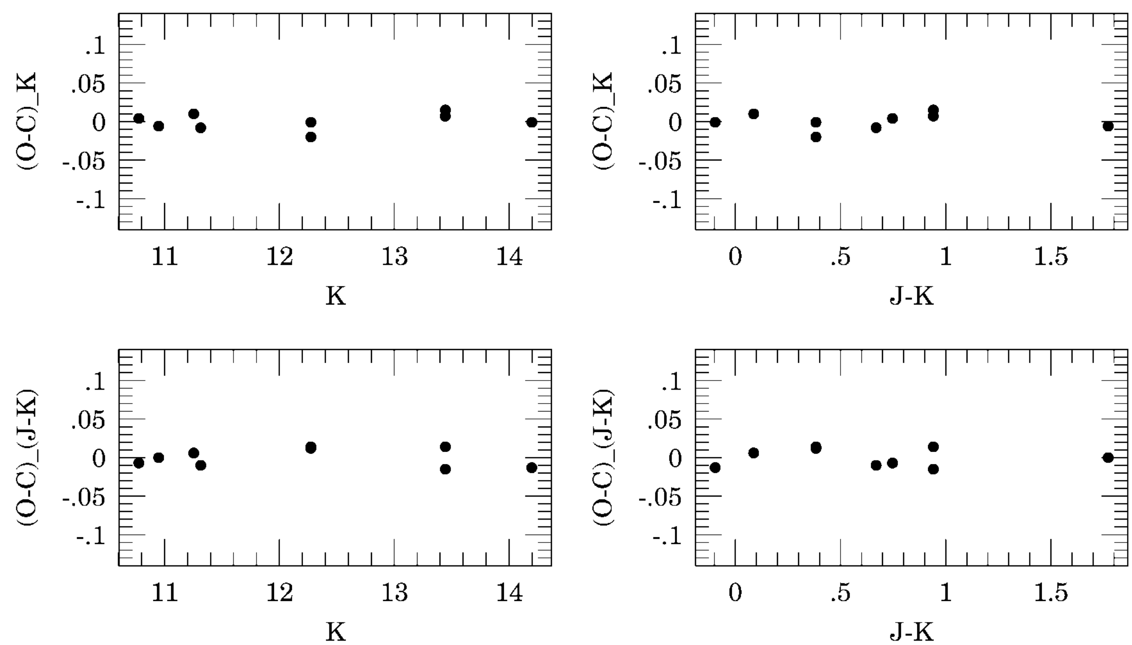

FIG. 1.—Observed minus calculated K-band magnitudes and $J-K$ colors for standard stars, as a function of magnitude and color

As can be seen, the color coefficients in the transformation equations are close to 1 and 0, which means that our instrumental system matches the standard UKIRT system very well. The residuals did not exceed 0.02 mag and did not show any dependence on color or brightness (see Fig. 1). The total error of our transformations, in particular, on the zero point of the K and J magnitudes, was estimated to be less than 0.03 mag.

In order to perform an external check on the accuracy of the zero point of our photometry, we searched the 2MASS database[2] for stars with accurate measurements and common to our data. Altogether, 19 such stars were found. Before comparing the results we needed to transform our data into the system used by 2MASS (Carpenter 2001). After doing this, we found the following differences between our photometry and the 2MASS data: -0.01 ± 0.04 and 0.00 ± 0.05 in K magnitude and $J-K$ color, respectively. Another independent check on the zero point of our K-band photometry can be done comparing the mean brightness of the red clump stars derived in this paper (see next section) to that of Alves et al. (2002). Alves et al. (2002) give $\langle K \rangle_{\rm Koornneef} = 16.974$ mag, while we obtain $\langle K \rangle_{\rm UKIRT} = 16.895$ mag. After converting both values to the K_s 2MASS system (Carpenter 2001) and correcting for the geometry of the LMC as discussed by van der Marel et al. (2002; our fields are about 0.025 mag closer than those observed by Alves et al.), we found that our photometry is brighter by about 0.001 mag than that presented by Alves et al. This excellent agreement of our present K-band photometry with Alves et al. and with another very recent study by Sarajedini et al. (2002) reassures us that systematic uncertainties on the photometric zero points are very small in both studies.

[2] See http://www.ipac.caltech.edu/2mass.

4. RESULTS

In Figure 2 we present the observed K versus $J-K$ color-magnitude diagrams for our two LMC fields, calibrated to the UKIRT system. It can be appreciated that the faintest stars that we were able to measure have K-band magnitudes of about 20.5. In both diagrams, the outstanding structural feature is the red clump, at a K magnitude of about 17. The signal-to-noise ratio for stars at the magnitude level of the red clump was calculated to be around 50. To our knowledge, these are the deepest infrared color-magnitude diagrams ever obtained in the LMC. Besides the red clump, many other features can be identified, including the main sequence and red giant branch. A detailed discussion of the different stellar populations appearing in these diagrams will be the subject of another study.

In order to derive the mean observed K-band magnitudes of the red clump stars in both fields, all stars having $J-K$ colors in the range from 0.35 to 0.80 mag and K-band magnitudes in the range from 16 to 18 were selected.

The histograms of the K-band magnitudes were derived for each field by using bins of 0.05 mag. Then the function (Paczyński & Stanek 1998)

$$n(K) = a + b(K - K^{\rm max}) + c(K - K^{\rm max})^2 + \frac{N_{\rm RC}}{\sigma_{\rm RC}\sqrt{2\pi}} \exp\left[-\frac{(K - K^{\rm max})^2}{2\sigma_{\rm RC}^2}\right], \quad (1)$$

consisting of the Gaussian function component representing the distribution of red clump stars superimposed on a second-order polynomial function approximating the stellar background, was fitted to the data. The total number of stars measured in our fields and the number of stars in our fitting boxes are indicated in Table 1.

In order to check on how our derived mean red clump star K-band magnitudes could potentially depend on the size of the box used for the selection of the stars for the construc-

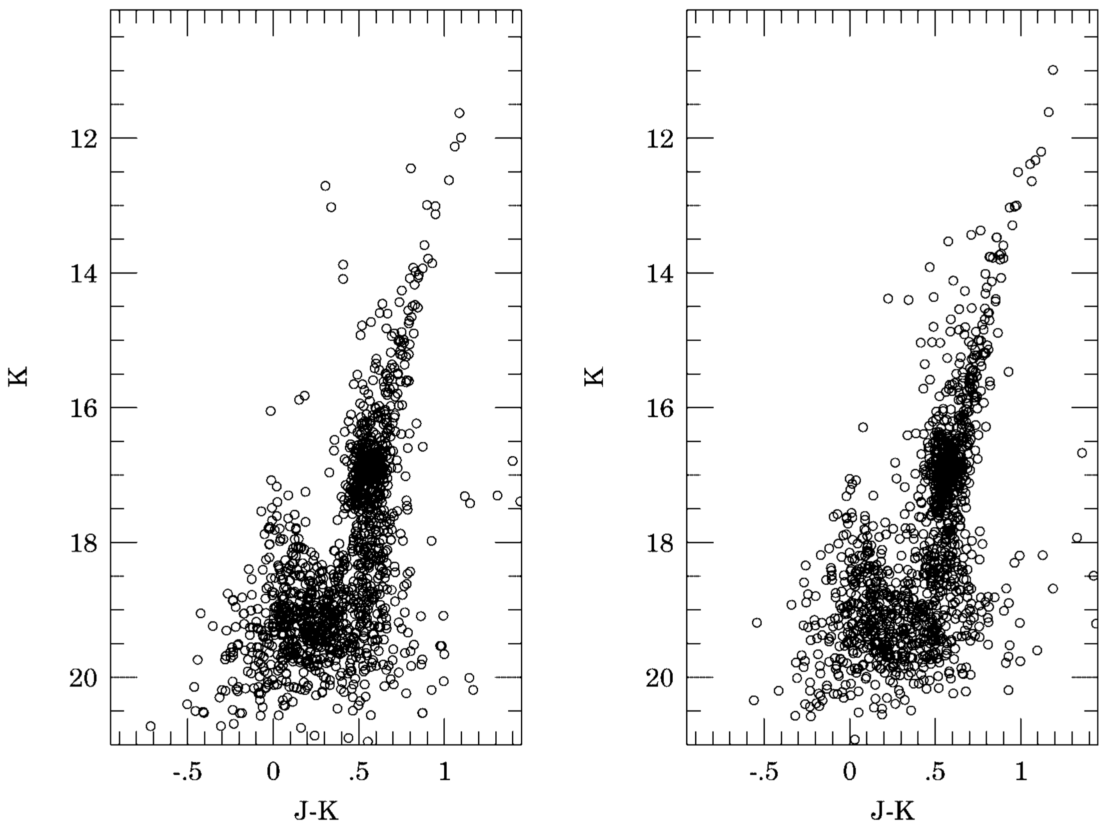

FIG. 2.—K, $J-K$ near-infrared color-magnitude diagram for the fields FI and FII (*left and right panels, respectively*; see Table 1). The most conspicuous feature is the red clump at $K \approx 17$ and $J-K \approx 0.6$ mag. Photometry goes down to about $K = 20.5$, and the signal-to-noise ratio at the red clump magnitude is about 50. The main sequence and red giant branch are also clearly delineated by the data.

tion of the histograms, we changed this box by 0.1 mag in color and 0.3 mag in magnitude (larger changes would be clearly unreasonable from the inspection of the color-magnitude diagrams) and repeated the whole procedure. As a result of this exercise, we found no significant change in the derived mean magnitudes of the red clump stars for either field.

As a result of our fits, we derive for the mean red clump K-band magnitudes 16.893 ± 0.011 mag for field I and 16.898 ± 0.010 mag for field II. The same procedure yields mean J-band magnitudes of 17.498 ± 0.012 and 17.512 ± 0.011 mag, respectively, for the two fields.

For both filters, the values for fields I and II are clearly in very good agreement. This is consistent with the fact that our fields are located very close to each other (the distance between them is smaller than $20'$) and no differential depth effect due to the slight tilt of the LMC bar with respect to the line of sight should be expected at such small angular differences. It is therefore justified to merge, for a given filter, the data of the two fields into one diagram in order to improve the statistical error on our results. We do this in Figure 3, and Figure 4 shows the fits of function (1) to the combined data, in both filters. From these fits, we derive as our final, adopted values for the mean K- and J-band magnitudes of red clump stars in the LMC, 16.895 ± 0.007 and 17.507 ± 0.009 mag, respectively.

In order to apply appropriate extinction corrections to these observed mean K- and J-band magnitudes, we adopted a value of $E(B-V) = 0.152$ mag, corresponding to our observed fields, from the OGLE II map of extinction in the LMC (Udalski et al. 1999). These maps were determined using the mean brightness of the red clump stars as tracers of the fluctuations of the mean reddening. The zero point was adopted from three different previous studies of inter-

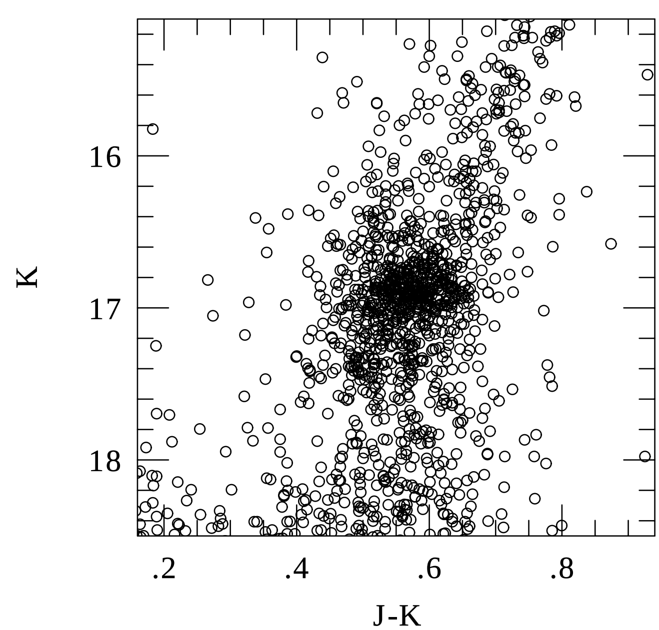

FIG. 3.—Combined K, $J-K$ color-magnitude diagram for the two observed fields, on a magnified scale that allows a better appreciation of the red clump structure.

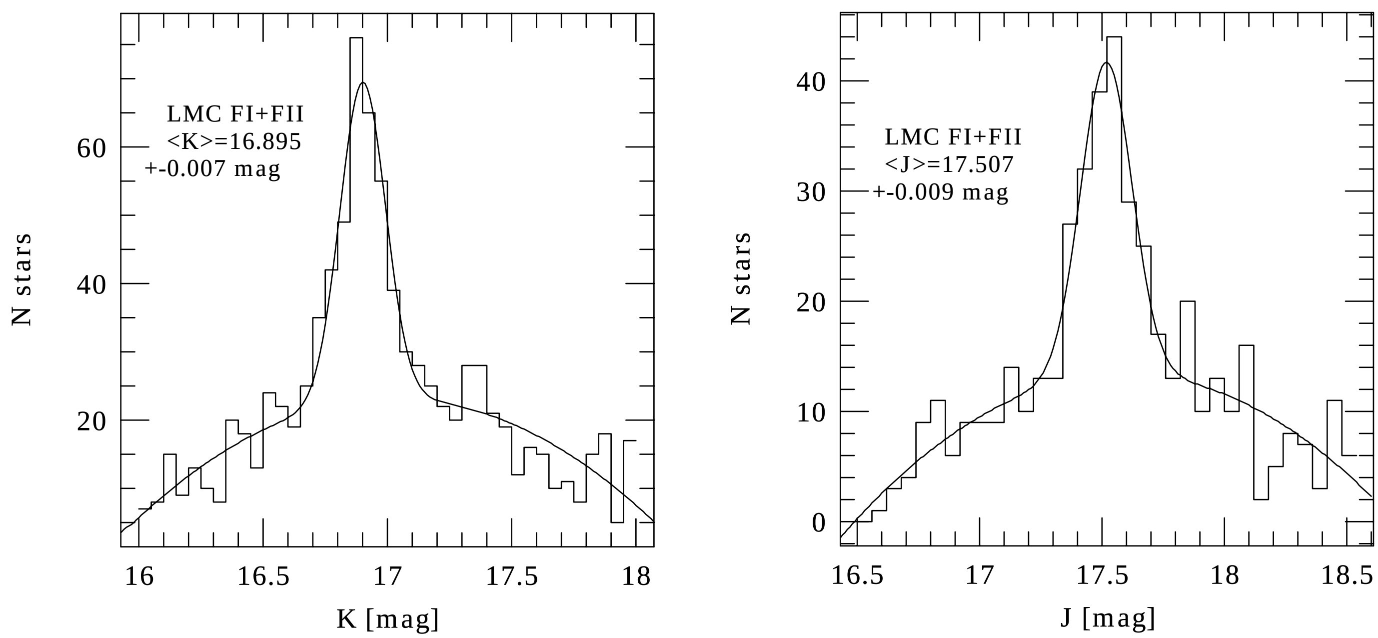

FIG. 4.—Gaussian and polynomial fits, according to eq. (1), applied to the stars in a box around the red clump in observed fields (see text for details). Sharp and well-defined peaks at a *K*-band magnitude of 16.895 and at a *J*-band magnitude of 17.507 are obtained from the data, with excellent statistics.

stellar extinction based on OB stars (Udalski et al. 1998; Lee 1995) and colors of RR Lyrae stars (Walker 1993). As noted by Udalski et al. (1999), all zero points were consistent within a couple thousand magnitudes. The absolute calibration of these maps was checked by comparing the observed *I*-band magnitudes of the red clump stars with the extinction-free magnitudes of red clump stars in clusters and field stars around them in the outer parts of the LMC (Udalski 1998), again showing very good agreement (to within 0.01 mag). Therefore, we adopt as an error on the reddenings derived from these maps the value of 0.02 mag as given by Udalski. We note that from a different study (Harris, Zaritsky, & Thompson 1997) there is an indication that the uncertainty on the reddening might be somewhat larger (about 0.035 mag), but such a slight difference would not have any significant effect on the budget of systematic errors affecting our current distance determination of the LMC.

Assuming the standard extinction curve [$A_K = 0.367E(B-V)$ and $A_J = 0.902E(B-V)$; Schlegel, Finkbeiner, & Davis 1998], we derive $A_K = 0.055$ mag and $A_J = 0.137$ mag, and therefore $\langle K \rangle_0 = 16.839$ and $\langle J \rangle_0 = 17.370$. To our knowledge, this is the first determination of the *J*-band mean magnitude of red clump stars in the LMC.

To compare our reddening-free mean *K*-band magnitude with the absolute *K*-band magnitude of the red clump stars from the *Hipparcos* sample (Alves 2000), we adopted the transformations between the Koornneef (1983), 2MASS, and UKIRT systems as derived by Carpenter (2001). It is worthwhile noting that there is practically no difference between *K* magnitudes in the UKIRT system to which our present data were transformed and the 2MASS K_s band [e.g., Carpenter 2001 gives the formula $(K_s)_{\rm 2MASS} = K_{\rm UKIRT} + 0.004(J-K)_{\rm UKIRT} + 0.002$, which results in a difference of about 0.004 mag for red clump stars between their $K_{\rm UKIRT}$ and K_s 2MASS magnitudes]. The correction to bring the red clump star magnitudes from the *Hipparcos* sample to the UKIRT system is 0.044 mag (Carpenter 2001). Applying this correction and *assuming that there is no population effect* on *K*-band red clump star magnitudes, we obtain an LMC true distance modulus of 18.487 ± 0.008 (random) $\pm$ 0.045 (systematic) mag. The systematic error on this result contains contributions from the uncertainty of the *Hipparcos*-calibrated absolute magnitude of red clump stars (0.03 mag), our current photometric zero point (0.03 mag), the uncertainty of the transformations between the different infrared systems (0.01 mag), and the uncertainty of the assumed reddening (0.02 mag).

If we adopt the van der Marel et al. (2002) geometrical model of the LMC, the corresponding distance of the LMC barycenter is 18.501 ± 0.008 (random) $\pm$ 0.045 mag (systematic).

5. DISCUSSION

Population effects on red clump star absolute magnitudes in different environments, including the solar neighborhood and the LMC, have been studied in some detail by Girardi et al. (1998) and by Girardi & Salaris (2001). In particular, under the assumption of a star formation history (SFH) and chemical evolution model for the solar neighborhood and the LMC, the latter authors found from population synthesis models that the distance moduli derived from a comparison of the mean magnitude of the red clump stars in the LMC to the corresponding mean magnitude of the red clump stars in the *Hipparcos* sample should be corrected by −0.03, 0.2, and 0.3 mag in *K*, *I*, and *V*, respectively, in order to compensate for the difference in metallicity and age between these two environments. A corresponding −0.03 mag correction has been applied by Alves et al. (2002) to their *K*-band data to allow for the population effect. Applying the same correction, our LMC barycenter distance result becomes 18.471 mag, in excellent agreement with their result.

Unfortunately, a discussion of the accuracy of such corrections was not presented in Girardi & Salaris (2001). An estimation of the uncertainties on these corrections should be based on population synthesis calculations performed for very different SFHs and chemical evolution models and should also take into account current uncertainties on the input physics of the stellar models used, which is a task far beyond the scope of this paper. However, we can make a rough estimate of the uncertainties of population corrections using the published simulations of Girardi et al (1998) and Girardi & Salaris (2001) for the *I* band. In spite of the fact that they performed their simulations for a very limited range of possible SFHs and chemical evolution models, their data show that changing these parameters one can obtain changes in the synthetic mean brightness of red clump stars of 0.115 mag (see Table 4 in Girardi & Salaris 2001). This is in agreement with the error estimate of about 0.1 mag for the model calculation results that was earlier given in Girardi et al. (1998, their § 5). So far, no similar data for the *K* band are available, but it seems reasonable to assume that the current uncertainty on the population correction in the *K* band may be of an order similar to what is extracted from the work of Girardi and coworkers for the *I* band. It is therefore of great importance to reduce the current uncertainty on population corrections for red clump stars, particularly in near-infrared bands, in order to make these objects truly superb standard candles. We note, for example, that Udalski (1998, 2000) derived an *I*-band population correction for LMC red clump stars of only 0.04 mag, based on a thorough study of red clump stars in LMC clusters, which is quite different from the 0.2 mag correction derived from the models of Girardi & Salaris, suggesting that there is still room for significant improvement in the future from both the model and the observational sides. A reduction of these uncertainties is likely to reconcile the apparent discrepancies of the LMC distance modulus obtained in the past by different workers from data in different bands. We expect that our ongoing near-infrared work on red clump stars in other Local Group galaxies that span a range in environmental properties will lead, in the near future, to such an improved empirical calibration of the dependence of red clump star magnitudes on the stellar ages and metallicities.

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