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THE ARAUCARIA PROJECT: DEPENDENCE OF MEAN *K*, *J*, AND *I* ABSOLUTE MAGNITUDES OF RED CLUMP STARS ON METALLICITY AND AGE[1]

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ABSTRACT

As a part of our ongoing Araucaria Project on the improvement of stellar distance indicators we present deep near-infrared *JK* imaging of several fields in four Local Group galaxies: LMC, SMC, and the Carina and Fornax dwarf galaxies. These data were obtained under excellent seeing conditions at the European Southern Observatory Very Large Telescope and New Technology Telescope. We determine the mean red clump star magnitudes in the *J* and *K* bands in the four galaxies. A comparison of the extinction-corrected *K*-band red clump star magnitudes with the tip of the red giant branch magnitude, the mean RR Lyrae star *V*-band magnitude, and the mean *K*-band magnitude of Cepheid variables at a period of 10 days (for the LMC and SMC) strongly suggests that the red clump star absolute *K*-band magnitude has a very low (if any) dependence on metallicity over the broad range of metallicities covered by our target galaxies. This finding is in contrast to the mean *I*- and *J*-band red clump star magnitudes, which do have a clear metallicity dependence and which we calibrate from our data. Excellent agreement with the former calibration of the red clump *I*-band magnitude dependence on metallicity of Udalski is found from our new data. We use the Galactic cluster *K*-band red clump star data of Grocholski & Sarajedini to demonstrate that the *K*-band red clump star absolute magnitude also has very little (if any) dependence on age over an age range of about 2–8 Gyr. The present study therefore provides clear evidence that the mean *K*-band magnitude of red clump stars is an excellent distance indicator, with very small (if any) population corrections to be applied over a large range in metallicity and age. Our findings imply that present-day population corrections calculated from models are only accurate at a ± 0.15 mag level, which is a great achievement in itself but not accurate enough for high-precision distance scale work. We determine the distances to all our target galaxies from the *K*-band red clump magnitude, with very small statistical uncertainties. Comparing these distances with those coming from the observed mean *I*-band magnitudes of the red clump stars, we find evidence that there is likely to be a problem in the photometric calibration of the local, solar neighborhood red clump star *K*- or *I*-band magnitudes, which amounts to some 0.2 mag. A redetermination of the absolute photometric calibration of the *Hipparcos*-observed nearby red clump stars seems necessary to resolve this problem and put the derivation of absolute distances to Local Group galaxies from their red clump stars on a firmer basis.

Key words: distance scale — galaxies: distances and redshifts — galaxies: individual (Fornax, Carina) — Magellanic Clouds — stars: intermediate population

1. INTRODUCTION

We have recently started on a long-term observational program called the Araucaria Project, which intends to check on the systematics and true capabilities of several stellar methods for distance measurement, using our basic strategy to apply such stellar techniques of distance determination to a common sample of galaxies with widely different environmental properties and to compare the results. This should eventually lead to a clear picture about the true capabilities of the different methods and their dependence on environmental properties such as metallicity and age, and it will help us select, calibrate, and apply those techniques that give the most accurate results. A more detailed description of the Araucaria Project can be found in Gieren et al. (2001).

The helium-burning intermediate-age red clump stars are particularly interesting and important in our studies. The main advantage in using these stars as standard candles is their small range of observed brightnesses in any given photometric band and the fact that they are very numerous in the solar neighborhood. About 1000 red clump stars have trigonometric parallaxes measured by the *Hipparcos* satellite with an accuracy of better than 10%, which made it possible to calibrate this method with an unprecedented accuracy (Paczyński & Stanek 1998; Alves 2000).

The main concern about using any object as a distance indicator is related to possible population effects, which might affect its brightness in different environments. Observations of red clump stars in clusters in the Magellanic

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Clouds indicate that the dependence of the mean *I*-band magnitude on age is practically negligible (within ± 0.05 mag) for the age range 2–9 Gyr (Udalski 1998). Detailed studies of the dependence of $\langle I \rangle^{\rm RC}$ on metallicity were performed using a large set of nearby red clump stars with spectroscopic metallicity determinations obtained by McWilliams (1990). Within the range of metallicities covered by the nearby red clump stars ($-0.5 < [{\rm Fe/H}] < 0.1$) the slope of the brightness-metallicity relation in the *I* band turned out to be a small but nonnegligible 0.14 mag dex^{-1} (Udalski 2000a).

Important progress was made by Alves (2000), who calibrated the absolute magnitudes of a large sample of *Hipparcos*-observed nearby red clump stars. An outstanding and obvious advantage of using the *K* band is that it practically eliminates any dependence of the obtained results on the adopted reddening. Alves (2000) also showed that the *K*-band magnitude of red clump stars does not seem to depend in any significant way on metallicity in the range from -0.5 to 0.0 dex. The results of the very recent work of Grocholski & Sarajedini (2002) also suggest that the mean magnitude of red clump stars in the *K* band may be an excellent standard candle, and, therefore, the step of taking the method to the near-infrared wavelengths is of a profound importance.

Encouraged by these first results, we decided to perform deep near-infrared imaging of selected fields in four Local Group galaxies, the LMC, SMC, and the Carina and Fornax dwarf spheroidals, in order to study in more detail how the mean *K* and *J* absolute magnitudes of red clump stars depend on their metallicities and/or ages. The very broad range of these environmental properties covered by our target galaxies was expected to be very useful for this purpose. In this paper we report on the results of this study.

2. OBSERVATIONS AND CALIBRATIONS

The data presented in this paper were collected with the European Southern Observatory (ESO) Very Large Telescope (VLT) equipped with the ISAAC infrared camera. In our chosen setup, the field of view was about $2\farcm5 \times 2\farcm5$, with a scale of $0\farcs148$ pixel^{-1}. The observations were performed on two photometric nights (2001 November 9 and 10). The seeing was about $0\farcs5$ and $1''$ during the first and second nights, respectively. The *J* and *Ks* observations for two fields in Fornax and two fields in Carina were secured on the first night. In addition, *Ks* images were obtained for a third field in the Carina galaxy in this first night of excellent seeing. During the second night *J* and *Ks* imaging was performed for two new fields in Carina and two additional fields in Fornax. We also obtained *J*-band data for the third field in Carina, observed in *Ks* on the first night. Table 1 gives information about the coordinates of our chosen fields and the number of red clump stars found in each of them.

In order to account for the frequent sky level variations in the infrared domain, especially in the *K* band, the observations were performed with a jittering technique. In the *Ks* filter we did five consecutive 12 s integrations (DITs) in any given sky position before moving the telescope by about $20''$ to a different position. Twenty-four and 78 such jittering positions obtained for the Carina and Fornax galaxies resulted in a total net exposure time of 24 and 78 minutes, respectively. The observations in the *J* band were made in a similar fashion. The total net exposure times for Fornax and Carina in this filter were 480 and 240 s during the first night and 800 and 360 s during the second night.

TABLE 1
OBSERVED FIELDS

Field	R.A. (J2000.0)	Decl. (J2000.0)	$N_{\rm RC}$
Fornax:			
FI	02 40 08.7	−34 11 28.0	82
FII	02 40 30.8	−34 25 13.5	204
FIII	02 39 32.9	−34 34 24.2	291
FIV	02 39 35.8	−34 25 37.4	242
Carina:			
FI	06 41 26.9	−50 58 33.4	46
FII	06 41 14.3	−51 00 32.6	39
FIII	06 40 59.8	−50 59 11.4	47
FIV	06 41 57.8	−50 54 33.6	31
FV	06 42 09.3	−50 55 09.1	28
LMC:			
FI	05 33 39.5	−70 09 36.5	464
FII	05 33 53.8	−70 04 01.9	494
FIII	05 22 42.9	−69 31 46.2	542
SMC:			
FI	00 43 44.5	−73 17 56.1	252
FII	00 44 05.2	−73 20 49.2	219

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

In order to accurately transform our data to the standard system, we secured eight and six observations of standard stars from the UKIRT system (Hawarden et al. 2001) on the first and second night, respectively, at a variety of air masses. These standard stars were chosen to span a broad range in colors bracketing the colors of the red clump stars in our fields. Aperture photometry of the standard stars was performed with the DAOPHOT program using apertures with radii of 16 pixels. Transformation coefficients were derived for each night. The accuracy of the zero points was calculated to be about 0.025 mag.

The data reductions were performed in an exactly analogous manner as in Pietrzyński & Gieren (2002). In brief, the sky was subtracted from the images, using a two-step process implying the masking of stars with the XDIMSUM IRAF package. After flat fielding and stacking into final images the PSF photometry was performed with the DAOPHOT and ALLSTAR programs, following the procedure described in detail in Pietrzyński, Gieren, & Udalski (2002). Aperture corrections were derived using about 10–20 relatively bright and isolated stars, after iteratively removing all stars from their neighborhood. The final aperture corrections were adopted as the median taken from all measurements and typically had a rms scatter of about 0.015 mag.

A more detailed description of the observations, data reduction, and calibration procedures, together with a discussion of the morphology of near-infrared color-magnitude diagrams, will be presented in Pietrzyński, Gieren, & Udalski (2003).

As part of the same project we observed 10 different fields in the LMC and SMC on three nights with the ESO New Technology Telescope (NTT) in the *J* and *Ks* filters. We have already used a part of these data to derive the distance to the LMC using *K* - band photometry of red clump stars (Pietrzyński & Gieren 2002). The detailed description of the complete set of data collected for the Magellanic Clouds will

be presented in a separate paper (Pietrzyński et al. 2003). Here we use photometry obtained with the ESO NTT on two nights for three fields in the LMC and two fields in the SMC to study the magnitudes of red clump stars in these galaxies. Basic information on the data is given in Table 1. Observations, reductions, and calibrations of these Magellanic Cloud data were performed in the same manner as for the data obtained for the Fornax and Carina dwarf galaxies. The accuracy of the derived zero points for the two NTT observing nights was better than 0.03 mag. It is worthwhile noting that the instrumental systems at both the NTT and the VLT are identical, which obviously helped us to obtain very homogenous data for all four galaxies discussed in this paper.

3. MEAN *K*- AND *J*-BAND RED CLUMP MAGNITUDES

The near-infrared K versus $J-K$ color-magnitude diagrams around the red clump region are shown in Figure 1 for our four target galaxies. The relatively large number of red clump stars found in our four fields in Fornax (see Table 1) allowed us to derive their mean K-band magnitudes individually for each field in this galaxy. We did this by selecting the stars with K-band magnitudes in the range from 18.3 to 20.3 mag and $J-K$ colors in the range from 0.3 to 0.85 mag and deriving the histogram of their K-band magnitudes in bins of 0.06 mag for each field. Then function (1), which consists of a Gaussian component representing the red clump stars distribution and a second-order polynomial function approximating the stellar background, was fitted to the data following a procedure originally introduced by Paczyński & Stanek (1998):

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

The same procedure was applied for deriving the mean red clump star magnitudes in the J band. The results are presented in Table 2. It can be appreciated that the four independent measurements of the mean J- and K-band red clump magnitudes obtained on the two different observing nights are in very good agreement. We therefore decided to merge the data in order to improve the statistics. The fits of function (1) to the histograms of the K and J magnitudes of red clump stars from the combined data are displayed in Figure 2. The corresponding results of $\langle K \rangle = 19.215 \pm 0.013$ and $\langle J \rangle = 19.687 \pm 0.014$ were finally adopted as the mean K- and J-band apparent magnitudes of red clump stars in the Fornax dwarf galaxy.

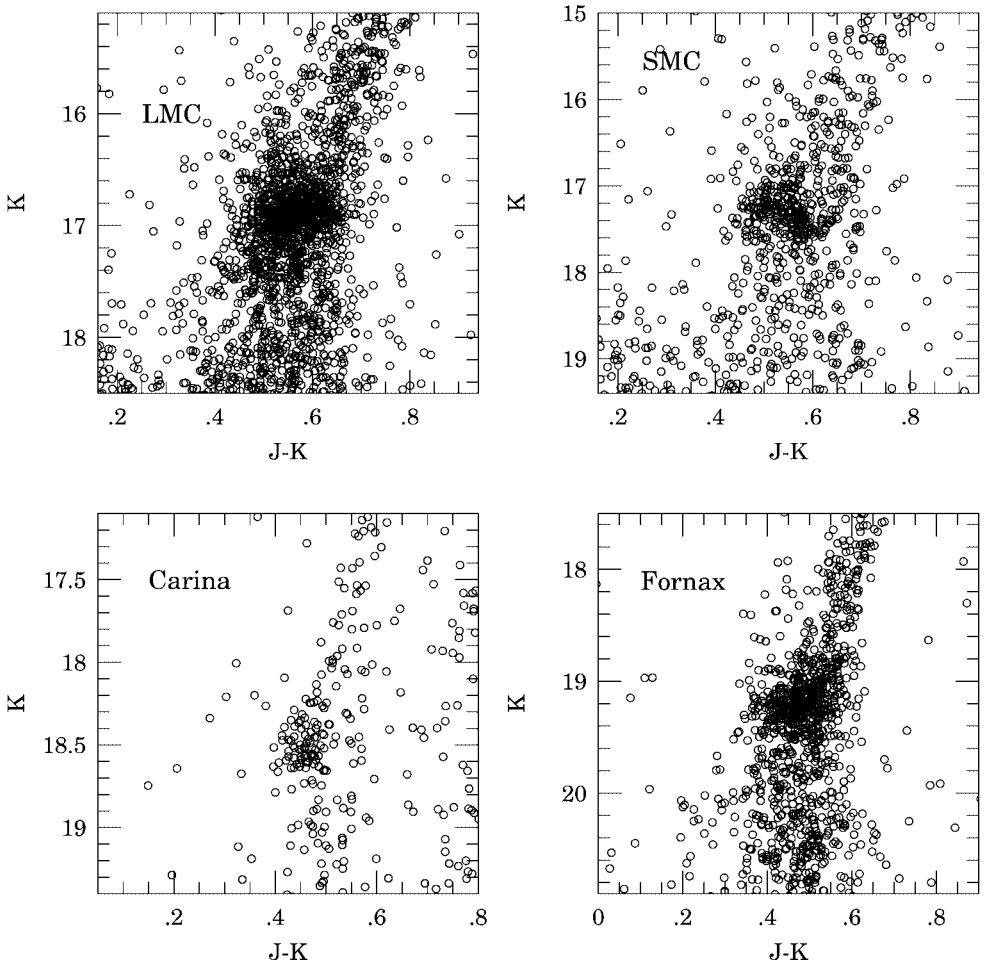


FIG. 1.—K, $J-K$ near-infrared color-magnitude diagrams for the LMC, SMC, Carina, and Fornax. Data have been combined from the different fields observed in each galaxy (see Table 1).

TABLE 2
MEAN J AND K MAGNITUDES OF RED CLUMP STARS IN FORNAX, CARINA, LMC, AND SMC

Field	$\langle K \rangle$	σ_K	$\langle J \rangle$	σ_J
Fornax:				
FI	19.26	0.05	19.72	0.05
FII	19.227	0.016	19.691	0.017
FIII	19.213	0.016	19.680	0.016
FIV	19.192	0.021	19.668	0.019
All data	19.215	0.013	19.687	0.014
Carina:				
Night 1	18.540	0.015	18.969	0.023
Night 2	18.51	0.04	18.99	0.05
All data	18.533	0.015	18.970	0.014
LMC:				
FI	16.893	0.013	17.508	0.009
FII	16.898	0.010	17.523	0.016
FIII	16.892	0.010	17.450	0.008
All data	16.894	0.007	17.472	0.007
SMC:				
FI	17.369	0.026	17.866	0.020
FII	17.339	0.020	17.84	0.03
All data	17.346	0.018	17.857	0.020

Using the same approach, we derived $\langle J \rangle$ and $\langle K \rangle$ for red clump stars in the FI and FII fields in the SMC and the FIII field in the LMC. Appropriate data for the fields FI and FII in the LMC were adopted from Pietrzyński & Gieren (2002). Again, very good agreement of the red clump star magnitudes for the different fields in LMC and SMC, respectively, was found, justifying the procedure to merge the data of the individual fields. This led to the following adopted red clump star magnitudes: $\langle K \rangle_{\rm LMC} = 16.894 \pm 0.007$, $\langle J \rangle_{\rm LMC} = 17.472 \pm 0.007$, $\langle K \rangle_{\rm SMC} = 17.346 \pm 0.018$, $\langle J \rangle_{\rm SMC} = 17.857 \pm 0.020$ mag. The corresponding fits are displayed in Figure 3.

It is worthwhile noticing that our $\langle K \rangle_{\rm LMC}$ on the UKIRT system is in very good agreement with $\langle K \rangle_{\rm LMC} = 16.974$ derived by Alves et al. (2002), on the Koorneef system (see Pietrzynski & Gieren 2002 for more details).

Our fields in the Magellanic Clouds are located so close (within about $0\overset{\circ}{.}5$) to the centers of these galaxies that any geometrical corrections to the red clump star magnitudes of the different fields are expected to be very small. We checked this by applying the geometrical model of van der Marel et al. (2002) for the LMC and that of Groenewegen (2000) for the SMC. The results were consistent with our previous estimations of the red clump star mean magnitudes to within 0.01 mag (e.g., clearly less than the accuracy of our zero-point measurements), justifying our procedure to merge the

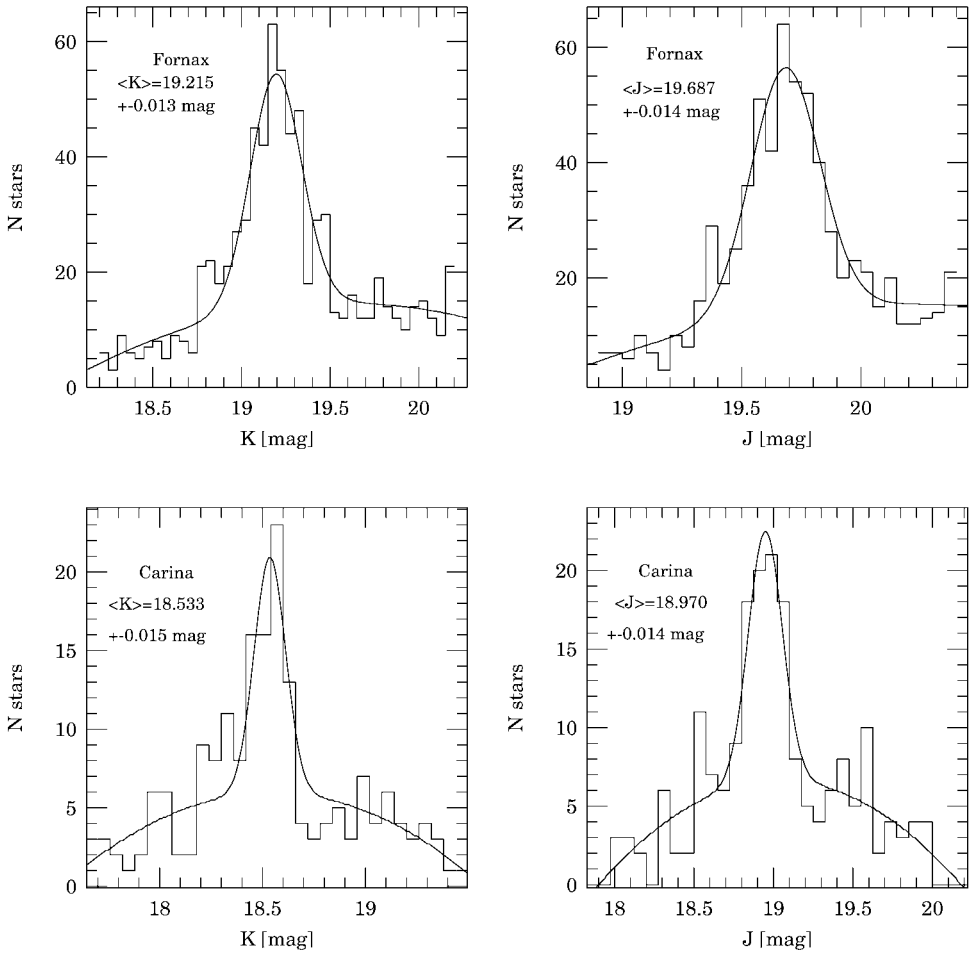


FIG. 2.—Gaussian and polynomial fit, according to eq. (1), applied to the stars in a box around the red clump in the Fornax and Carina dwarf galaxies (see text for details). Sharp and well-defined peaks at for the mean K- and J-band magnitudes are obtained from the data, with excellent statistics.

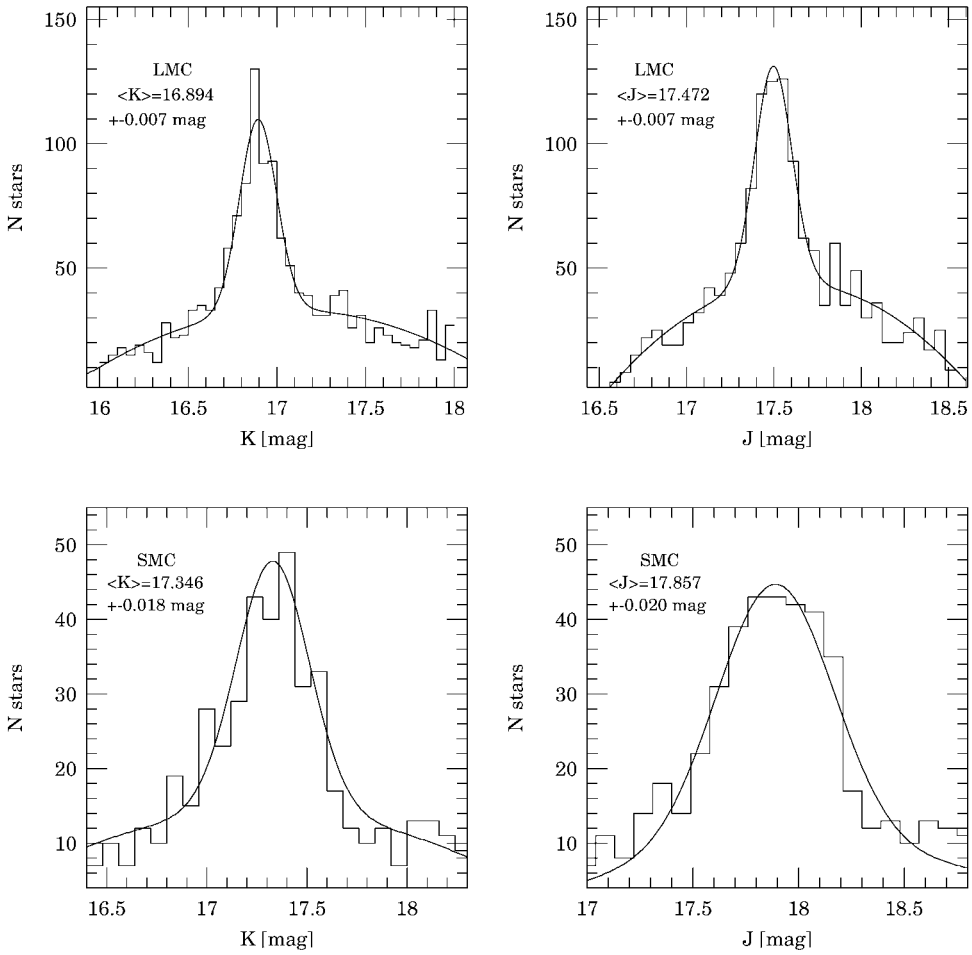


FIG. 3.—Same as in Fig. 2, but for LMC and SMC

data of our individual fields in the LMC and SMC without previously applying corrections for the geometrical structures of the Clouds.

In the case of Carina the number of red clump stars we found is not large enough to derive mean red clump star magnitudes for the individual fields. However, it should be noted that all our five selected fields are located very close each other (the distance between them is less than 10′), so we decided to merge the observations for the two nights and different fields and to derive the mean K and J magnitudes of the red clump stars in the same manner as we did for Fornax and the Magellanic Clouds. The fit of function (1) to the combined data for Carina yielded as our adopted final red clump star mean magnitudes for this galaxy $\langle K \rangle = 18.533 \pm 0.015$ and $\langle J \rangle = 18.970 \pm 0.014$ mag. The fits in the case of Carina are shown in Figure 2.

4. COMPARISON WITH OTHER DISTANCE INDICATORS

In Table 3 we give the reddening-corrected $\langle K_0 \rangle$ magnitudes of the red clump stars in the LMC, SMC, Carina, and Fornax. For comparison we also give the I-band magnitudes of the tip of the red giant branch (TRGB) and the mean V-band magnitude of RR Lyrae stars in these galaxies, taken from the literature. The magnitudes for the TRGB and the RR Lyrae stars in the Magellanic Clouds and Carina dwarf galaxy were adopted from Udalski (2000b). $\langle I^{\rm TRGB} \rangle$ for Fornax was taken from Bersier (2000). The reddenings toward the Fornax and Carina galaxies were derived from the Schlegel, Finkbeiner, & Davis (1998) extinction maps, yielding $E(B-V)_{\rm Car} = 0.06 \pm 0.01$ mag and $E(B-V)_{\rm For} = 0.03 \pm 0.01$ mag, respectively. Extinction corrections to our fields in the Magellanic Clouds were applied by adopting the appropriate values of $E(B-V)$ from the OGLE II extinction maps in the LMC [Udalski et al. 1999a; $E(B-V)_{\rm FI,FII} = 0.152$, $E(B-V)_{\rm FIII} = 0.115$ mag] and in the SMC [Udalski et al. 1999b; $E(B-V)_{\rm FI,FII} = 0.089$] using the reddening law as given by Schlegel et al. (1998).

TABLE 3
MEAN OBSERVED MAGNITUDES OF MAJOR DISTANCE INDICATORS IN OUR TARGET GALAXIES

Galaxy	$\langle K_0^{\rm RC} \rangle$ (mag)	$\langle I_0^{\rm TRGB} \rangle$ (mag)	$\langle K_0^{\rm Cep,10d} \rangle$ (mag)	$\langle V_0^{\rm RRLyrae} \rangle$ (mag)
LMC.....	16.844 ± 0.007	14.33 ± 0.02	12.79 ± 0.02	18.91 ± 0.01
SMC.....	17.313 ± 0.018	14.83 ± 0.02	13.28 ± 0.02	19.44 ± 0.02
Carina.....	18.511 ± 0.015	16.03 ± 0.05	...	20.61 ± 0.03
Fornax.....	19.204 ± 0.013	16.65 ± 0.05	...	...

NOTE.—$\langle V_0^{\rm RRLyrae} \rangle$ at $[{\rm Fe/H}]_{\rm LMC} = -1.6$ dex (Alcock et al. 1996).

Finally, the mean $\langle K_0 \rangle$ magnitudes of Cepheids at a pulsation period of 10 days in the Magellanic Clouds were calculated using the relations provided by Groenewegen (2000). These are also given in Table 3.

For our further discussion we adopt -0.5 dex for the metallicity of intermediate-age populations in the LMC (Bica et al. 1998; Smecker-Hane et al. 1999), and -1.0 dex for the SMC (see Udalski 2000b for a discussion). For Fornax we assume [Fe/H] $= -1.0$ (Saviane, Held, & Bertelli 2000; Tolstoy et al. 2002). From spectroscopic metallicity determinations of 52 stars in Carina, Smecker-Hane et al. (1999) derived a mean metallicity of red giants in this galaxy of -2.0 dex. More recently Tolstoy et al. (2002), using high-resolution spectra obtained with the UVES at the VLT for five stars, argued that the mean metallicity of red giant stars in the Carina dwarf galaxy is less metal-poor and about -1.6 dex. We adopt the mean from these two determinations for Carina, e.g., -1.8 dex.

It has been shown by empirical investigations (Lee, Freedman, & Madore 1993; Udalski 2000b) that the *I*-band magnitude of the TRGB is independent of population effects in the range of ages and metallicities covered by our four target galaxies. Moreover, comparisons between TRGB distances and Cepheid distances in many galaxies (Lee et al. 1993; Kennicutt et al. 1998; Ferrarese et al. 2000; Udalski 2000b) showed excellent agreement between these two distance indicators. Therefore, by studying the difference of $\langle K_0^{\rm RC} \rangle$ and $\langle I_0^{\rm TRGB} \rangle$ as a function of metallicity and age, we should be able to detect any population effects on $\langle K_0^{\rm RC} \rangle$. Figure 4 shows such a comparison as a function of metallicity. It can be appreciated from this diagram that there is clearly no systematical trend in the difference of the red clump *K*-band magnitude and the TRGB *I*-band magnitude with metallicity. A linear regression leads to $\langle K_0^{\rm RC} \rangle - \langle I_0^{\rm TRGB} \rangle = 2.51$, with a dispersion of only 0.04 mag. An analogous comparison of the red clump star mean *K*-band magnitude with $\langle V_0^{\rm RRLyrae} \rangle$, where the RR Lyrae mean *V*-band magnitude has been corrected for a metallicity slope of 0.18 (see Udalski 2000b and references therein) yields a very similar result (see Fig. 4, *right*).

Another, independent test of a possible trend of $\langle K_0^{\rm RC} \rangle$ with metallicity can be done using the 2MASS near-infrared photometry of Cepheids in the Magellanic Clouds (Groenewegen 2000). Here it is worthwhile noticing that there is practically no difference between the 2MASS *Ks*- and the *K*-band magnitudes in the UKIRT system to which our data have been transformed (Carpenter 2001). Using the P-L relations published by Groenewegen (2000), we derive $\langle K_0^{\rm RC} \rangle - \langle K_0^{\rm Cep,P=10d} \rangle = 4.05 \pm 0.02$ for the LMC and 4.03 ± 0.03 for the SMC, again indicating that this magnitude difference does not depend on metallicity (at least in the metallicity range covered by LMC and SMC).

All our comparisons seem to indicate that $\langle K_0^{\rm RC} \rangle$ *does not depend, or depends very little, on population effects in the very broad metallicity range* ($-1.8 <$ [Fe/H] < -0.5) *and the very different star formation histories covered by our four target galaxies*. This is in very good agreement with the results of Alves (2000), who also found that the $\langle K_0^{\rm RC} \rangle$ absolute magnitude of red clump stars in the solar neighborhood does not show any significant trend with metallicity in the range from -0.5 to 0.0 dex.

In principle, the dependence of $\langle K_0^{\rm RC} \rangle$ on metallicity and age can also be checked with star clusters containing sufficient red clump stars and spanning a range in ages and metallicities. Unfortunately, the number of clusters with available accurate infrared photometry is very low at the present time. A first attempt to study the behavior of $\langle K_0^{\rm RC} \rangle$ in a sample of Galactic clusters was recently performed by Grocholski & Sarajedini (2002). They took infrared data for 14 open clusters from the 2MASS database and found an over-all agreement of the data with model predictions about the dependence of the *K*-band red clump star magnitude on age and metallicity. However, the accuracy of their results was clearly limited by the low number of red clump stars in the studied clusters and the distance uncertainties of the clusters inherent in the MS-fitting technique of distance determination. The typical accuracy of $\langle M_0^{\rm RC} \rangle$ they were able to achieve was about 0.11–0.2 mag. Still, at least a crude check on the possible age dependence of the red clump star *K*-band absolute magnitude is possible from the Grocholski & Sarajedini cluster data. We did this by selecting clusters having ages in the range from 2 to 9 Gyr (covering the age range of the red clump stars in the target galaxies of this paper). Three clusters (NGC 6819, M67, and Be 39) were identified. Their metallicitis fall in the range covered by the *Hipparcos* red clump star sample; therefore, no dependence of their $M_K^{\rm RC}$ on metallicity is expected (Alves 2000). In Figure 5 we show $M_K^{\rm RC}$ for these clusters versus the cluster age. Within the error bars on the absolute magnitudes, no indication of a systematic trend of the red clump star *K*-band absolute magnitude with age is visible in this diagram, suggesting that the red clump star *K*-band absolute magnitude is not only very insensitive to metallicity but also to age over a broad range of ages.

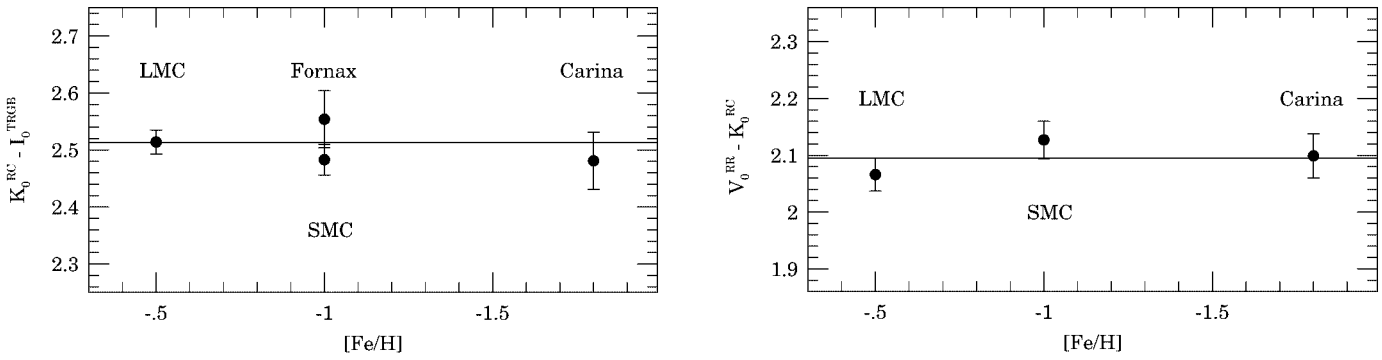


FIG. 4.—Comparison of the red clump star mean *K*-band magnitude $\langle K_0^{\rm RC} \rangle$, with $\langle I_0^{\rm TRGB} \rangle$ (*left*) and with $\langle V_0^{\rm RRLyrae} \rangle$ corrected for a metallicity dependence of $0.18 \times$ [Fe/H] (*right*). See text for more details.

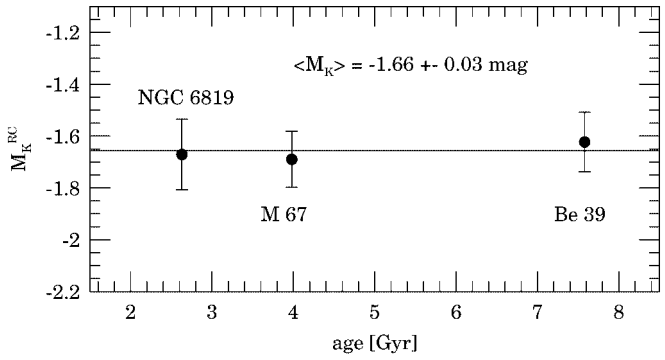


FIG. 5.—Absolute red clump K-band magnitude $M_K^{\rm RC}$ from Grocholski & Sarajedini (2002) for open clusters having ages in the range from 2 to 9 Gyrs displayed as a function of age. The metallicities of these clusters all lie in the range covered by the *Hipparcos*-observed red clump stars, so no dependence of $M_K^{\rm RC}$ on metallicity is expected (Alves 2000). The data suggest no significant dependence of $M_K^{\rm RC}$ on age over the age range covered by these clusters.

5. POPULATION DEPENDENCE OF RED CLUMP STAR MAGNITUDES IN THE I AND J BANDS

We can now trace out the population dependence of the $\langle I\rangle_0^{\rm RC}$ and $\langle J\rangle_0^{\rm RC}$ magnitudes very accurately, studying the relative magnitudes of these stars in our target galaxies. The I-band data for the red clump stars in the different galaxies were taken from the literature (Udalski et al. 1998, 2000; Udalski 2000b for LMC, SMC, and Carina; Bersier 2000 for Fornax) and were dereddened in exactly the same way as our infrared data presented in this paper. The mean I-, J-, and K-band magnitudes, corrected for reddening, are presented in Table 4.

As can be seen in Figure 6, the differences of $\langle I\rangle_0^{\rm RC}-\langle K_0^{\rm RC}\rangle$ and $\langle J\rangle_0^{\rm RC}-\langle K_0^{\rm RC}\rangle$ are both strongly correlated with metallicity. Least-squares fits to a straight line give the following slopes: 0.09 ± 0.02 and $0.13+-0.02$ mag dex^{-1} for the metallicity dependence of $\langle J\rangle_0^{\rm RC}$ and $\langle I\rangle_0^{\rm RC}$, respectively. This result is in amazing agreement with the former result of Udalski (2000a) on the metallicity dependence of the red clump star I-band magnitude, who had obtained $\langle I\rangle_0^{\rm RC}=(0.14\pm0.04)\times[{\rm Fe/H}]+{\rm const}$, from a study of the *Hipparcos* red clump stars with high-quality spectroscopic metallicity determinations in the range from 0 to -0.5 dex. The dependence of $\langle J\rangle_0^{\rm RC}$ on metallicity is found to be slightly weaker than that of $\langle I\rangle_0^{\rm RC}$, as one could expect from the effective wavelengths of the J band (1.2 μm) and I band (0.8 μm).

TABLE 4
MEAN IJK MAGNITUDES OF RED CLUMP STARS IN OUR TARGET GALAXIES

Galaxy	$\langle K_0\rangle$ (mag)	$\langle J_0\rangle$ (mag)	$\langle I_0\rangle$ (mag)
LMC.....	16.844	17.358	17.97
SMC.....	17.313	17.776	18.35
Carina.....	18.511	18.916	19.46
Fornax.....	19.204	19.659	20.24

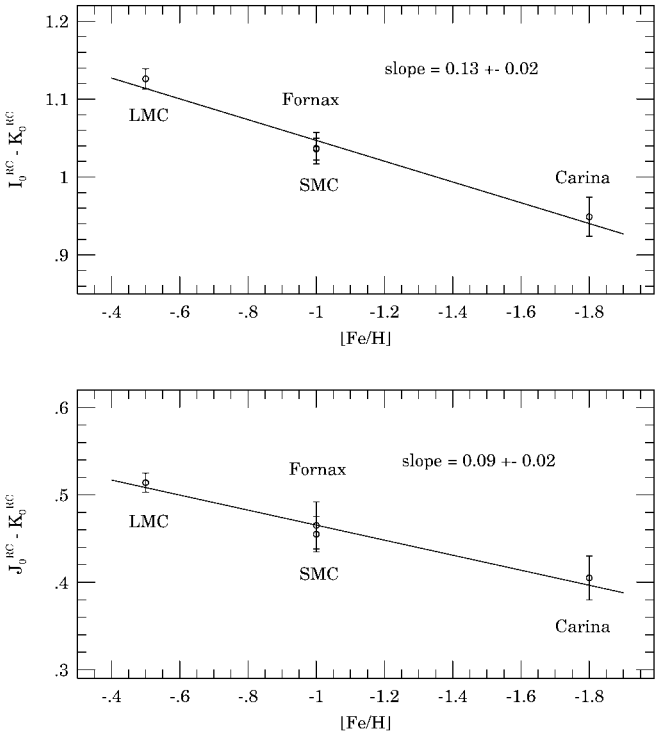


FIG. 6.—Comparison of $\langle I_0^{\rm RC}\rangle$ and $\langle J_0^{\rm RC}\rangle$ with the metallicity-independent K-band red clump magnitude. The observed slopes in these diagrams reflect a clear dependence of both $\langle I_0^{\rm RC}\rangle$ and $\langle J_0^{\rm RC}\rangle$ on metallicity.

6. DISCUSSION

In Figure 7 we present the difference between the relative $\langle I_0\rangle$ magnitudes of red clump stars derived with respect to the LMC and corrected for their metallicity dependence and their $\langle K_0\rangle$ magnitudes (also relative to the LMC). It is clearly seen that in all environments *except the solar neighborhood* there is excellent agreement between the relative brightnesses of the red clump stars in these two bands. This

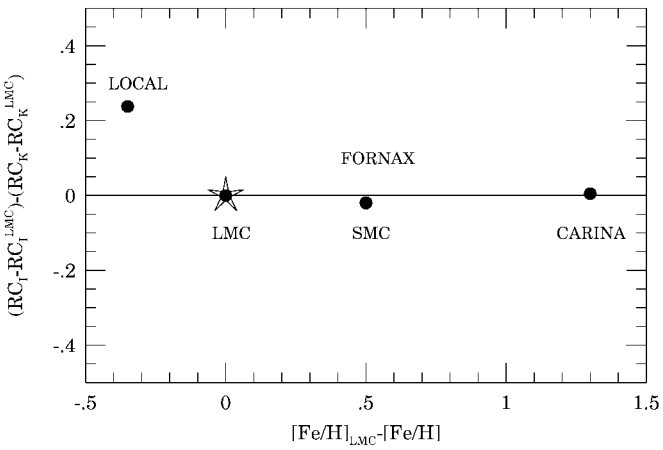


FIG. 7.—Plot of the difference between the relative (with respect to the LMC) $\langle I_0^{\rm RC}\rangle$ (corrected for its metallicity dependence) and the corresponding relative $\langle K_0^{\rm RC}\rangle$ against metallicity for solar neighborhood red clump stars and those in the four target galaxies of the present study. It can be seen that in all environments this difference is very close to zero, the exception being the solar neighborhood red clump stars. This suggests that the photometric data for the *Hipparcos*-observed red clump stars probably have a zero-point error in the order of 0.2 mag in either the K or the I band.

finding suggests that there may be a very significant zero-point error, on the order of 0.2 mag, in either the *K*- or *I*-band photometry of the local *Hipparcos* red clump stars (of course, it is also possible that the current local calibrations have significant errors in both bands).

Transforming our *K*-band data to the Koorneef system with the transformations provided by Carpenter (2001) and using the *K*-band absolute calibration of Alves (2000), we derive the following true distance moduli from *K*-band red clump star magnitudes to the target galaxies of the present study:

1. 18.498 ± 0.007 mag (LMC),
2. 18.967 ± 0.018 mag (SMC),
3. 20.165 ± 0.015 mag (Carina dwarf galaxy),
4. 20.858 ± 0.013 mag (Fornax dwarf galaxy).

The quoted uncertainties are the statistical errors of our distance determinations. The LMC distance result is in excellent agreement with our own former result (Pietrzynski & Gieren 2002), which was based on a smaller number of fields, and with the recent independent distance determinations to the LMC from the red clump star *K*-band photometry of Alves et al. (2002) and Sarajedini et al. (2002).

The above distance moduli are to be compared with those obtained from *I*-band data corrected for their metallicity dependence: 18.26 ± 0.07 mag for the LMC (Udalski 2000b), 18.71 ± 0.07 for the SMC (Udalski 2000b), 19.96 ± 0.08 for Carina (Udalski 2000b), and 20.60 for Fornax (Bersier 2000).

We then find, as already discussed and shown in Figure 7, that there is a near-constant difference of about 0.2 mag between the distances derived to our target galaxies from the *K*- and *I*-band magnitudes of red clump stars, using the local solar neighborhood calibrations of Alves (2000) for the *K* band and of Udalski (2000a) for the *I* band. It will be of obvious importance to check on these calibrations in the near future to find out whether this way the results from both bands can be reconciled.

Finally, our current empirical results provide a very strong test on the accuracy of the so-called population corrections derived from stellar models and assuming a star formation history and chemical evolution history for both the solar neighborhood and a given target galaxy (Girardi & Salaris 2002). Using the Girardi & Salaris corrections for the *K* band, one obtains $d_{SMC} - d_{LMC} = 0.43$ mag and $d_{CAR} - d_{LMC} = 1.53$ mag. If we compare these values with the empirical results for the distance difference between SMC and LMC (0.47 ± 0.03 mag from RC in *K* without corrections, 0.50 ± 0.04 mag from TRBG, 0.52 ± 0.03 from RR Lyrae stars, and 0.49 ± 0.03 from Cepheids in the *K* band) and for the distance difference between Carina and the LMC (1.70 ± 0.05 from TRGB, 1.71 ± 0.03 from RR Lyrae stars, and 1.67 ± 0.03 from the RC in K), we can conclude that the current accuracy of the predictions of such models is about 0.1–0.15 mag (see also the discussion in Pietrzyński & Gieren 2002). Although it is quite impressive that, in spite of the rather poorly known SFH and chemical evolution histories in these galaxies, one can get results from the models whose agreement with accurate empirical data is in the order of 0.1–0.15 mag, such an approach is clearly of less use for accurate distance determinations to nearby galaxies at the present time.

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