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THE ARAUCARIA PROJECT: THE DISTANCE TO THE LOCAL GROUP GALAXY IC 1613 FROM NEAR-INFRARED PHOTOMETRY OF CEPHEID VARIABLES[1]

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ABSTRACT

We have measured accurate near-infrared magnitudes in the *J* and *K* bands of 39 Cepheid variables in the irregular Local Group galaxy IC 1613 with well-determined periods and optical *VI* light curves. Using the template light curve approach of Soszyński, Gieren, & Pietrzyński, accurate mean magnitudes were obtained from these data, which allowed us to determine the distance to IC 1613 relative to the LMC from a multiwavelength period-luminosity solution in the optical *VI* and near-IR *JK* bands with an unprecedented accuracy. Our result for the IC 1613 distance is $(m - M)_0 = 24.291 \pm 0.035$ (random error) mag, with an additional systematic uncertainty smaller than 2%. From our multiwavelength approach, we find for the total (average) reddening to the IC 1613 Cepheids $E(B - V) = 0.090 \pm 0.019$ mag, which is significantly higher than the foreground reddening of about 0.03 mag, showing the presence of appreciable dust extinction inside the galaxy. Our data suggest that the extinction law in IC 1613 is very similar to the Galactic one. Our distance result agrees, within the uncertainties, with two earlier infrared Cepheid studies in this galaxy, of Macri et al. (from *HST* data on 4 Cepheids) and McAlary et al. (from ground-based *H*-band photometry of 10 Cepheids), but our result has reduced the total uncertainty on the distance to IC 1613 (relative to the LMC) to less than 3%. With distances to nearby galaxies from Cepheid infrared photometry at this level of accuracy, which are currently being obtained in our Araucaria Project, it seems possible to significantly reduce the systematic uncertainty of the Hubble constant, as derived from the *HST* Key Project approach, by improving the calibration of the metallicity effect on PL relation zero points and by improving the distance determination to the LMC.

Subject headings: Cepheids — distance scale — galaxies: distances and redshifts — galaxies: individual (IC 1613) — infrared: stars

Online material: machine-readable tables

1. INTRODUCTION

Cepheid variables are the most important standard candles to calibrate the first rungs of the extragalactic distance ladder, out to some 30 Mpc. As young stars, Cepheids tend to lie in dusty regions in their spiral or irregular parent galaxies. As a consequence, Cepheid distances derived from the period-luminosity (PL) relation in optical photometric bands are quite sensitive to a precise knowledge of the total reddening, foreground and intrinsic, of their parent galaxy. While the Galactic foreground reddening toward any direction in the sky is usually well established, particularly in directions far away from the Galactic equator, the correct assessment of the reddening produced by dust extinction *intrinsic to the host galaxy* is usually a difficult task, and in most work on Cepheid distances based on optical data such an intrinsic contribution to the reddening has simply been ignored. Just for this one particular reason, it is clear that more accurate Cepheid distances to galaxies can be derived in near-infrared passbands, where dust absorption is small as compared to visual wavelengths, and the distance results become increasingly independent of errors in the assumed total reddenings.

[1] Based on observations obtained with the New Technology Telescope (NNT) at ESO La Silla for programs 074.D-0318(B) and 074.D-0505(B).

Efforts along these lines started in the early 1980s with the pioneering work of McGonegal et al. (1982) and Welch et al. (1985). Yet, an important obstacle to carrying out accurate Cepheid distance work in the infrared has been, until very recently, the lack of well-calibrated fiducial PL relations in the near-infrared *JHK* bands. This problem has now been solved by the work of Persson et al. (2004), who provided such well-calibrated relations for the LMC. Very recently, Gieren et al. (2005b) have also provided well-calibrated PL relations in the *JHK* bands for Milky Way Cepheids, which agree with the corresponding LMC relations when an improved version of their infrared surface brightness technique (Gieren et al. 1997, 1998) is used.

In the Araucaria Project, started by our group some time ago (Gieren et al. 2005c), we have conducted surveys for Cepheid variables in a number of galaxies in the Local Group and in the more distant Sculptor Group in order to investigate the effect of environmental properties on the PL relation and to improve the accuracy of Cepheids as distance indicators. While we are discovering Cepheids in optical photometric bands, where these stars are rather easy to detect due to their relatively large amplitudes and typical light-curve shapes (e.g., Pietrzyński et al. 2002a, 2004), the main goal of the program is to undertake near-infrared follow-up imaging of selected subsamples of Cepheids in our target galaxies to obtain accurate reddening information and thus to obtain more accurate distances than what is possible from optical (*VI*) data alone. Near-infrared PL relations from such Cepheids with existing information on their periods and *V* and/or *I* light curves can be obtained very economically because it is possible to obtain accurate mean *JHK* magnitudes for these stars from just one single-phase observation using the template light-curve approach of Soszynski et al. (2005). The success of this approach was recently demonstrated in the case of the Sculptor galaxy NGC 300 (Gieren et al. 2005a). For this galaxy, a combination of the PL relations obtained in the optical *VI* and infrared *JK* bands has allowed us to determine a distance that is practically unaffected by any remaining uncertainty on reddening. It was also shown in that paper that from the combined optical/near-infrared approach a total uncertainty as small as 3% can be obtained for the Cepheid distance (as measured relative to the LMC) for such a relatively nearby (2 Mpc) galaxy.

In the present paper, we apply the same approach to the Local Group dwarf irregular galaxy IC 1613. IC 1613 is a very important galaxy in the Araucaria Project because of the very low metallicity of its young stellar population, close to -1.0 dex (Skillman et al. 2003), making it the lowest metallicity galaxy in our sample. It is therefore a key object in our effort to determine the effect of metallicity on the Cepheid PL relation, as well as on other stellar distance indicators, such as blue supergiant stars (Kudritzki et al. 2003). A first survey for Cepheid variables in IC 1613 was carried out by Sandage (1971), who used photographic images previously obtained by Baade. Modern work on the Cepheid PL relation in IC 1613, in the optical *V* and *I* bands, has been carried out by the OGLE Project (Udalski et al. 2001), which discovered many new, previously unknown Cepheids in this irregular galaxy. More recently, Antonello et al. (2006) have extended this work to the *B* and *R* bands. From the work of the OGLE group, it could be established that the slope of the PL relation in optical bands is identical to the slope observed for the more metal-rich LMC Cepheids, arguing for a metallicity-independent slope of the PL relation. In the near-infrared, a pioneering paper on the distance of IC 1613 from *H*-band photometry of 10 Cepheids was published by McAlary et al. (1984) already 20 years ago; however, the uncertainty on this distance result was rather large due to the technical difficulties in obtaining accurate IR photometry at those times and the lack of an accurate calibrating PL relation. Much more recently, Macri et al. (2001) determined a near-infrared Cepheid distance to IC 1613 from *H*-band photometry of four variable stars obtained with NICMOS on board the *Hubble Space Telescope* (*HST*). The accuracy of this determination suffers, however, from the very small number of stars used in the PL solution. A main goal of the present study was to derive *truly accurate near-infrared PL relations for IC 1613*, based on a large number of well-observed and well-selected Cepheids (see § 3.2), and in this way reduce the current uncertainty on the distance to IC 1613 to the very small level of 3%–5% we achieved in our previous study of NGC 300.

We organized this paper in the following way: in § 2 we describe the observations, reductions, and calibration of our data; in § 3 we present the calibrated infrared mean magnitudes of the Cepheids in our selected fields in IC 1613 and determine the distance and reddening; in § 4 we discuss our results; and in § 5 we summarize the main results of this work and present some conclusions.

2. OBSERVATIONS, DATA REDUCTION, AND CALIBRATION

2.1. *Optical Data*

Our infrared observations of IC 1613 (see § 2.2) were obtained about 4 years after the OGLE-II optical observations (Udalski et al. 2001) of this galaxy. This long gap in time made it necessary to improve the periods of the Cepheids in order to calculate accurate $\langle K \rangle$ and $\langle J \rangle$ mean magnitudes from single-phase infrared observations with the method of Soszynski et al. (2005). For this purpose, three new *V*-band observations of IC 1613 with the 1.3 m Warsaw telescope located at Las Campanas Observatory were secured in September 2005. This telescope is equipped with a mosaic 8k$\times$8k detector, with a field of view of $35' \times 35'$ and a scale of $0\farcs25$ pixel^{-1}. Preliminary data reductions (i.e., debiasing and flat fielding) were done with the IRAF package.[2] The point-spread function photometry was obtained with the DAOPHOT and ALLSTAR programs, in an identical way as described in Pietrzyński et al. (2002a). Our photometry was then transformed to the standard system using the OGLE-II list of carefully calibrated stars in this galaxy (Udalski et al. 2001).

2.2. *Infrared Data*

The near-infrared data presented in this paper were collected with the European Southern Observatory (ESO) New Technology Telescope (NTT) telescope at La Silla, equipped with the SOFI infrared camera. In the setup we used (large field) the field of view was $4\farcm9 \times 4\farcm9$, with a scale of $0\farcs288$ pixel^{-1}. The gain and readout noise were 5.4 e ADU^{-1} and 0.4 e, respectively.

The data were obtained under two observational programs: 074.D-0318(B), 074.D-0505(B) (PI: G. Pietrzyński) as part of the Araucaria Project. Altogether, six different, slightly overlapping fields were observed through the *J* and *Ks* filters. Their location is shown in Figure 1, and the equatorial coordinates of their centers are given in Table 1.

Single deep *J* and *Ks* observations of our six fields were obtained under excellent seeing conditions during three different photometric nights. On these nights, we also observed a large number of photometric standard stars from the UKIRT system

[2] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation.

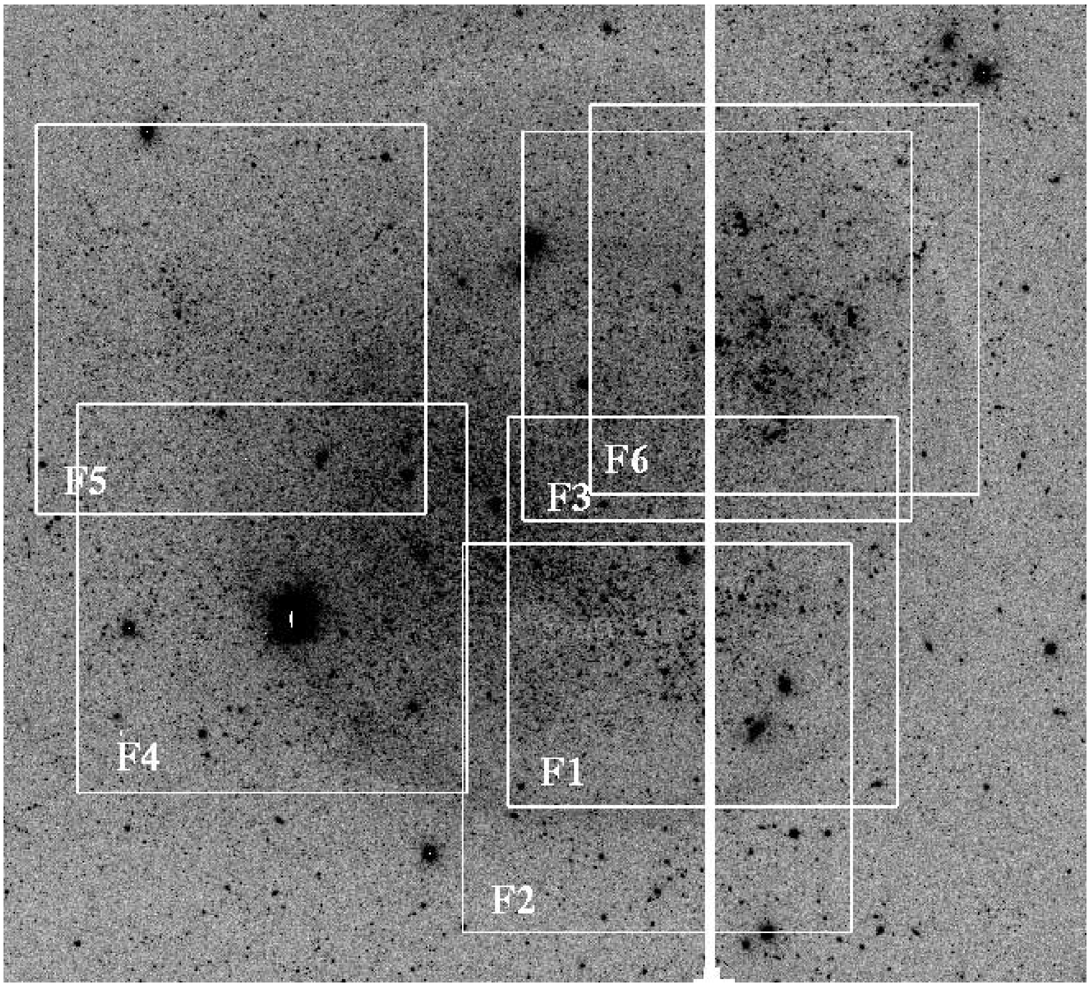

Fig. 1.—Location of the observed NTT fields in IC1613 on a *V*-band image of this galaxy, taken with the Warsaw 1.3 m telescope on Las Campanas.

(Hawarden et al. 2001). In order to account for the rapid sky level variations in the infrared domain, the observations were performed with a dithering technique. In the *Ks* filter, we obtained six consecutive 10 s integrations (DITs) at a given sky position and then moved the telescope by about 20″ to a different random position. Integrations obtained at 65 different dithering positions resulted in a total net exposure time of 65 minutes in this filter for a given field. In the case of the *J* filter, in which the sky level variations are less pronounced than in *K*, two consecutive 20 s exposures were obtained at each of 25 dithering positions, which corresponded to a total net exposure of about 17 minutes for any given field.

Sky subtraction was performed by using a two-step process implying the masking of stars with the XDIMSUM IRAF package in an analogous manner as described in Pietrzyński & Gieren (2002). Then the single images were flat-fielded and stacked into the final images. Point-spread function (PSF) photometry was obtained using DAOPHOT and ALLSTAR, following the procedure described in Pietrzyński et al. (2002b). In order to derive the aperture corrections for each frame, about 7–10 relatively isolated and bright stars were selected, and all neighboring stars were removed using an iterative procedure. Finally, we measured the aperture magnitudes for the selected stars with the DAOPHOT program using apertures of 16 pixels. The median from the differences between the aperture magnitudes obtained in this way, as well as the corresponding PSF magnitudes, averaged over all selected stars was finally adopted as the aperture correction for a given frame. The rms scatter from all measurements was always smaller than 0.02 mag.

In order to accurately transform our data to the standard system, a large number (between 8 and 15) of standard stars from the UKIRT system (Hawarden et al. 2001) were observed under photometric conditions at a variety of air masses, together with our six science fields. The standard stars were chosen to have colors bracketing the colors of the Cepheids in IC 1613. The aperture photometry for our standard stars was performed with DAOPHOT using the same aperture as for the calculation of the aperture corrections. Given the relatively large number of standard stars we observed on each night, the transformation coefficients were derived for each night. The accuracy of the zero points of our photometry was determined to be about 0.02 mag.

TABLE 1
Coordinates of the Centers of the Observed NTT SOFI Fields in IC 1613

Field	R.A.	Decl.
F1	01 04 58.9	02 05 48.5
F2	01 04 56.6	02 04 13.2
F3	01 04 59.6	02 09 23.9
F4	01 04 37.2	02 05 58.8
F5	01 04 35.1	02 09 29.4
F6	01 05 03.0	02 09 44.4

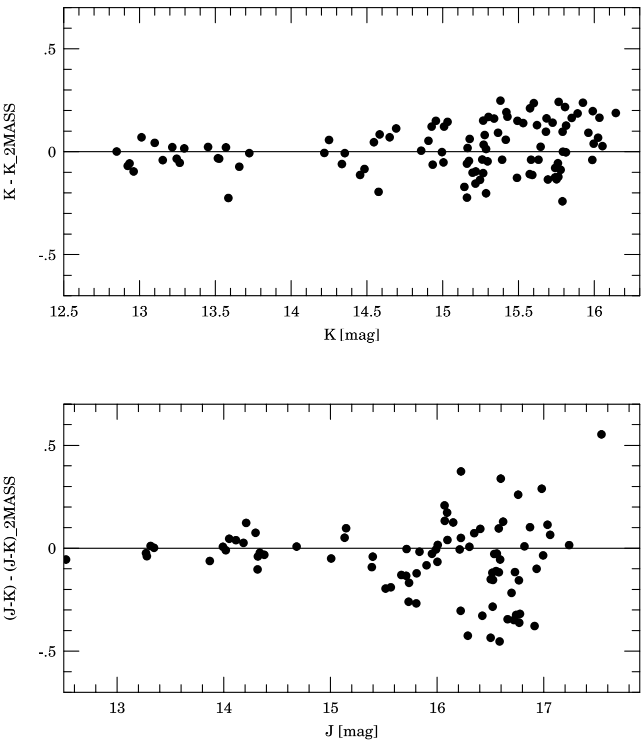

Fig. 2.—Comparison of our present photometry with the 2MASS data. In spite of the relatively large scatter toward the fainter magnitudes caused by the low accuracy of the 2MASS photometry of faint stars, no evident zero point offset either in K or in $J - K$ is present.

Since our six fields overlap (see Fig. 1), we were able to perform an internal check of our photometry, comparing the magnitudes of stars located in the common regions. In every case the independently calibrated magnitudes agree within 0.02–0.03 mag in both K and J filters. Unfortunately, we are not aware of any other deep near-infrared JK images obtained for IC 1613, so an external check of our photometry is not possible. However, the magnitudes of the bright stars in our fields can be compared with the 2MASS photometry. Figure 2 presents the difference between our K magnitudes and $J - K$ colors, and the corresponding 2MASS data for common bright stars. Before calculating these differences, we transformed our photometry, which had been calibrated onto the UKIRT system, to the 2MASS system using the equations provided by Carpenter (2001). In spite of the relatively large uncertainties of the 2MASS data for the fainter stars in Figure 2, it is appreciated that there is no evident zero-point offset either in K or in $J - K$, supporting the conclusion that both data sets are well calibrated, within 0.02–0.03 mag.

The pixel positions of the stars were transformed to the equatorial coordinate system using Digital Sky Survey (DSS) images. For this purpose, we used the algorithm developed and used in the OGLE project (Udalski et al. 1998). The accuracy of our astrometric transformations is better than 0.″3.

3. RESULTS

3.1. *The Cepheid Mean K- and J-Band Magnitudes*

In the six NTT SOFI fields observed in this project, 39 objects from the Cepheid list presented by Udalski et at. (2001) were identified. It is worth noticing that most of the (few) long-period OGLE II Cepheids in IC 1613 are located in our fields. Thanks to the depth of our infrared photometry, we were able to detect Cepheids with periods down to about 2 days.

TABLE 2

Journal of the Individual J and K Observations of IC 1613 Cepheids

ID	HJD (J)	J	σ_J	HJD (K)	K	σ_K
11446........	53,215.86015	16.997	0.009	53,215.80516	16.492	0.009
11446........	53,315.64411	17.400	0.016	53,315.58668	16.822	0.016
10421........	53,315.64411	19.551	0.060	53,315.58668	18.877	0.071
1987..........	53,370.57443	17.938	0.019	53,370.52660	17.593	0.024
736............	53,315.72831	17.833	0.018	53,315.67116	17.260	0.018

Note.—Table 2 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

In Table 2, we present the journal of individual observations of these 39 Cepheid variables. Most of them were observed only once. However, several objects located in the overlapping areas were observed twice. Before deriving the mean K and J magnitudes of the Cepheids from these data, we tried to improve the periods given by Udalski et al. (2001) using our new three-epoch optical observations, which are given in Table 3. For the long-period Cepheids ($P \gtrsim 5$), we could indeed improve the periods with these new data. However, for the variables with shorter periods the time elapsed between two sets of observations was too large for us to unambiguously count the number of elapsed cycles. For these Cepheids, we adopted the OGLE-II periods from Udalski et al. (2001).

The mean magnitudes were obtained from the template light-curve method of Soszyński et al. (2005), which uses the V-band phases of the individual near-IR observations and the light curves amplitudes in V and I to calculate the differences of the individual single-phase magnitudes to the mean magnitudes in J and K. For a detailed description of this technique, the reader is referred to that paper. It has been demonstrated by these authors that the mean K and J magnitudes of Cepheids can be derived from just one random-phase observation with an accuracy of 0.02–0.03 mag, provided that high-quality optical and infrared data and periods are available for the stars. In Table 4 we present the final intensity mean JK magnitudes of the 39 Cepheids in our fields, with their estimated uncertainties and their adopted periods. The last column contains remarks on some of the variables. V2, V6, etc., correspond to the numbering system introduced by Sandage (1971).

3.2. *Selection of the Final Sample*

In Figure 3, we show the optical V versus $V - I$ color-magnitude diagram of IC 1613 obtained from the OGLE-II data (Udalski et al. 2001) on which the locations of the Cepheids observed in the present study are marked. In Figure 4, we display the PL relations in the K and J bands which we obtain from the data of all the 39 Cepheids in Table 4. While the data define

TABLE 3

Journal of the Individual V-Band Observations of IC 1613 Cepheids

ID	HJD	V	σ_V
11446......................................	53,620.76797	18.385	0.009
11446......................................	53,621.75534	18.422	0.008
11446......................................	53,621.82741	18.412	0.008
10421......................................	53,620.76797	21.632	0.079
10421......................................	53,621.75534	21.648	0.069

Note.—Table 3 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

TABLE 4

Final Intensity Mean J and K Magnitudes of IC 1613 Cepheids

OGLE ID	P	$\log P$	$\langle J \rangle$	σ_J	$\langle K \rangle$	σ_K	Remarks
11446	41.87	1.62194	17.114	0.009	16.605	0.009	V20
10421	29.19	1.46529	19.694	0.060	19.029	0.071	PII, V47
1987	25.398	1.40480	17.715	0.019	17.405	0.024	V11
736	23.469	1.37049	17.745	0.018	17.256	0.018	V2
7647	16.488	1.21716	18.056	0.020	17.688	0.027	Blend
13738	16.420	1.21537	18.590	0.043	18.066	0.028	V18
13682	14.317	1.15585	16.815	0.010	15.818	0.005	Not Cepheid, V39
17473	13.154	1.11906	99.999	9.999	20.669	0.251	PII
7664	10.4390	1.01866	18.996	0.030	18.555	0.048	V16
926	9.4286	0.97445	19.109	0.028	18.736	0.036	V6
879	9.2130	0.96440	19.156	0.046	18.689	0.054	V25
13808	7.572	0.87921	19.591	0.092	19.160	0.058	
13759	7.3403	0.86571	19.272	0.074	18.832	0.112	V7
13709	6.741	0.82872	18.480	0.041	17.739	0.020	Blend
5037	6.3175	0.80055	19.824	0.065	19.484	0.127	
11604	5.8191	0.76486	19.685	0.051	19.133	0.097	
13780	5.5771	0.74641	19.973	0.137	19.256	0.069	V9
11831	5.0269	0.70130	19.902	0.063	19.532	0.111	
8146	4.5630	0.65925	20.306	0.075	19.730	0.122	
14287	4.365	0.63998	99.999	9.999	19.951	0.142	
12109	4.1364	0.61662	20.128	0.079	19.344	0.093	
13784	4.0657	0.60914	99.999	9.999	19.459	0.096	V10
11743	3.8953	0.59054	19.348	0.035	18.795	0.047	Blend, V53
8127	3.8444	0.58483	20.636	0.097	20.267	0.159	
2240	3.0733	0.48760	20.941	0.138	20.221	0.147	V35
18349	2.8700	0.45788	99.999	9.999	19.639	0.102	V29
19024	2.8418	0.45359	99.999	9.999	19.859	0.154	
12068	2.781	0.44420	20.013	0.060	19.339	0.091	Blend
2760	2.7123	0.43334	21.101	0.127	20.651	0.203	
10804	2.6629	0.42535	21.041	0.137	20.404	0.197	V48
12526	2.6310	0.42012	99.999	9.999	20.982	0.358	
7322	2.3378	0.36881	21.125	0.141	21.145	0.328	
6128	2.2578	0.35369	20.712	0.114	20.140	0.174	
8782	2.0930	0.32077	21.013	0.137	20.673	0.255	
5996	2.0682	0.31559	20.888	0.183	20.508	0.284	V60
2389	2.0286	0.30720	20.837	0.115	20.363	0.175	
13481	1.678	0.22479	99.999	9.999	21.226	0.392	
2771	1.3290	0.12352	99.999	9.999	20.193	0.150	FO
8173	1.3103	0.11737	20.587	0.099	20.020	0.130	FO

tight PL relations in both bands, there are some objects which clearly deviate from the bulk of the Cepheids in these diagrams, and which need individual discussion. These stars are indicated with open circles in Figure 4.

Star 13682 is most probably not a Cepheid variable (Sandage 1971; Antonello et al. 1999). Udalski et al. (2001) supported this conclusion from the position of this star on the V, $V-I$ color-magnitude diagram (CMD; see Fig. 3) and its abnormal location on the optical PL relations on which 13682 appears much brighter than other Cepheids with similar periods. This proves also true for its near-IR magnitudes illustrated in Figure 4. We therefore exclude this object for the distance determination.

Besides star 13682, the variables 13709, 11743, 12068, 8173, and 2771 are also very significantly brighter than other Cepheids with similar periods. The two latter Cepheids with their very short periods are almost certainly first-overtone pulsators. Due to the detection limit in our present near-infrared photometry we would not see fundamental mode pulsators at this very short period of about 1.3 days. The three other overbright Cepheids are probably blended by relatively bright stars. These Cepheids are also located above the Cepheid PL relations in the V and I bands (Udalski et al. 2001). In Figure 3, variable 11743 appears close to the red edge of the instability strip, while the heavily blended Cepheid 13709 lies outside the strip, supporting the blending hypothesis. For star 12068, unfortunately, no $V-I$ color is available.

The remaining two clearly deviating stars, 10421 and 17473, were already classified as Population II Cepheids by Udalski et al. (2001). Indeed, these stars are located about 2 mag below the IR Cepheid PL relations (see Fig. 4), which fully supports the conclusion about the Population II nature of these objects.

In the light of the arguments presented above, we decided to reject all these eight objects from the final sample of Cepheids used for the distance determination.

Finally, we would like to comment on the Cepheid designated 7647. Udalski et al. (2001) suspected this star to be a heavily blended Cepheid. Indeed, as can be seen in Figure 3, this star is located blueward toward the instability strip, suggesting that this variable is blended with a very bright blue star. In the infrared, Cepheid 7647 appears with normal flux and colors. This finding is consistent with the presence of a blue, unresolved companion star, which contaminates the optical but not the near-infrared photometry. We therefore retain this Cepheid in our final list of stars for the distance solution in the infrared. We remark that an

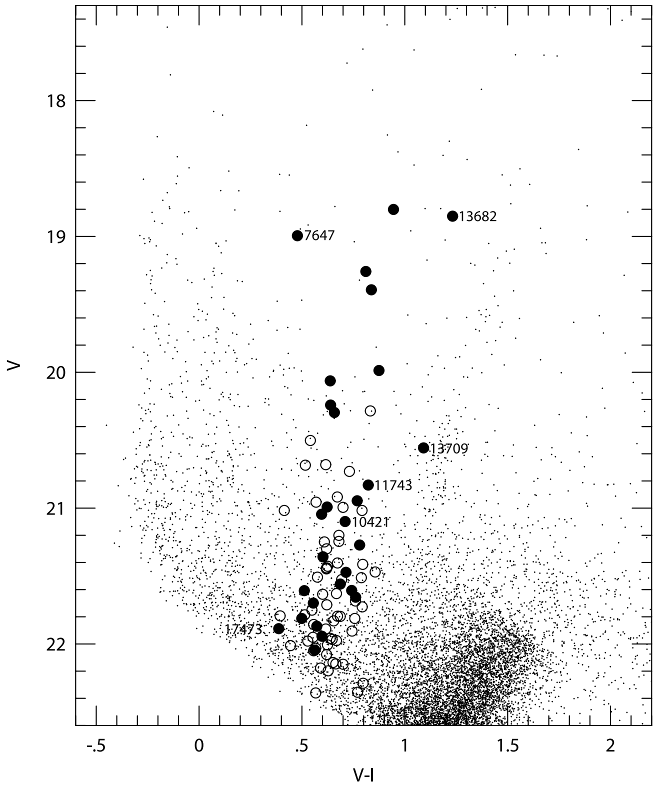

Fig. 3.—V, $V-I$ CMD for the stars in IC 1613 based on the OGLE-II data (Udalski et al. 2001). It is demonstrated that the Cepheids observed in infrared bands and used for distance determination in the present study (*stars marked with filled circles, without numbers*) uniformly cover the instability strip. Cepheids with filled circles and given OGLE-II identifications are discussed in the text. OGLE-II Cepheids not covered in our infrared study are marked with open circles.

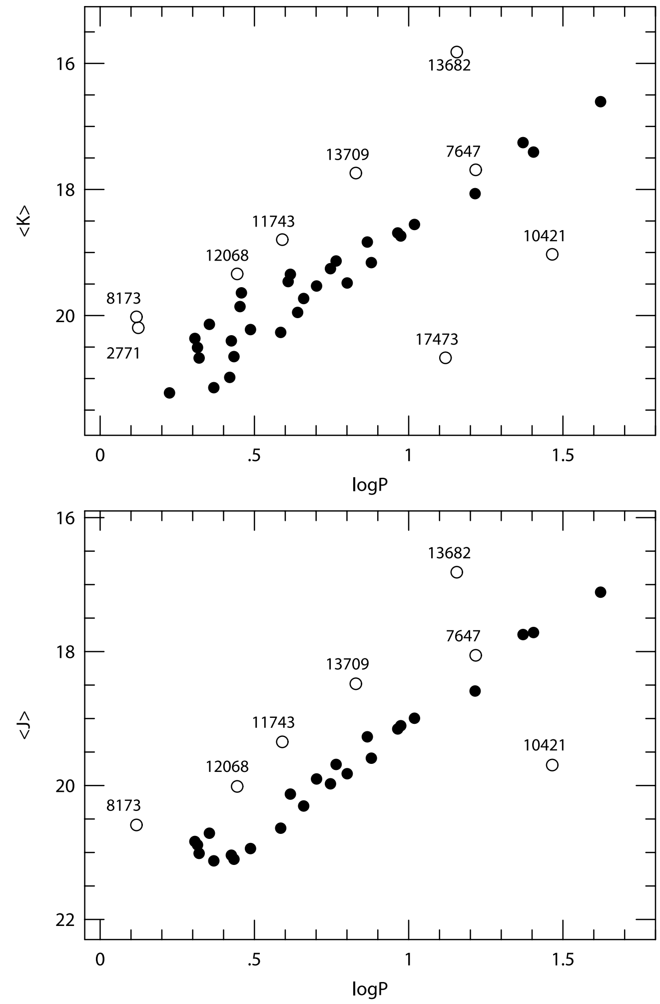

Fig. 4.—PL relations in the K and J bands, for all Cepheids presented in Table 3. The stars labeled with their OGLE-II identifications are mostly outliers and are discussed in the text.

omission of this star from the final sample would not significantly alter the results we present below.

The errors of the mean K-band magnitudes for Cepheids with $\log P < 0.5$ days become large due to (1) the relatively low accuracy of the K-band photometry for such a faint stars ($K > 20.5$ mag) and (2) the increasingly uncertain mean magnitude corrections for these stars, caused by their relatively noisy optical light curves and less accurate periods. We obtained linear regressions to the PL relations in the J and K bands for the whole sample, including the faintest stars and for the subsamples limited to the Cepheids with $\log P > 0.5$, finding very good agreement (to better than 1 σ) between the corresponding solutions. However, since the inclusion of the shortest period Cepheids in the solutions does increase the noise significantly, we decided to adopt $\log P = 0.5$ as a lower cut-off period for our solutions. This way, our final samples in J and K still comprise some 20 Cepheids with excellent photometry, which is sufficient for a very accurate determination of the distance to IC 1613.

3.3. *Determination of the Distance and Reddening*

The least-squares fits to the mean magnitudes of the Cepheids from our carefully selected final list yield the following slopes of the PL relations: -3.117 ± 0.044 in J and -3.148 ± 0.053 in K. The stated errors are 1 σ uncertainties. These values agree very well with the slopes of the PL relations for the LMC Cepheids in these bands derived by Persson et al. (2004) (-3.153 and -3.261 in J and K, respectively) and are consistent with the LMC values within the combined uncertainties. We therefore calculated the zero points of the Cepheid J- and K-band PL relations in IC 1613 by adopting the corresponding slopes from Persson et al. (2004). This yields the following results:

$$J = -3.153 \log P + (22.187 \pm 0.040),$$

$$K = -3.261 \log P + (21.827 \pm 0.045).$$

The adopted linear regressions to our K and J Cepheid data are shown in Figure 5. Before calculating, from the determined zero points, the relative distance of IC 1613 with respect to the LMC, we need to convert our PL relation zero-point magnitudes calibrated for the UKIRT system (Hawarden et al. 2001) to the NICMOS system, on which the corresponding LMC zero points were calibrated (Persson et al. 2004). According to Hawarden et al. (2001), there are just zero-point offsets between the UKIRT and NICMOS systems (e.g., no color dependence) in the J and K filters, which amount to 0.034 and 0.015 mag, respectively. After adding these offsets and assuming an LMC true distance modulus of 18.5 mag (see § 4 for discussion of this assumption), we derived the following distance moduli for IC 1613: 24.385 (J) and 24.306 mag (K) (see Table 5). The corresponding distance moduli in the optical V (24.572 mag) and I (24.488 mag) bands had been previously calculated from the OGLE-II data by Udalski et al. (2001) adopting the linear LMC Cepheid PL relations (Udalski et al. 1999; Udalski 2000).

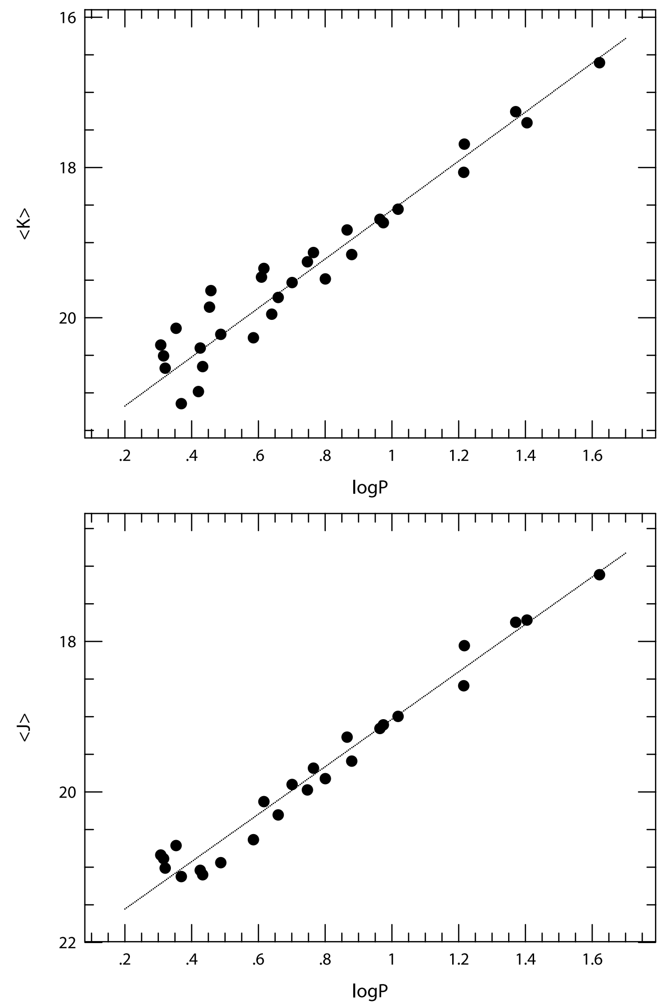

FIG. 5.—Final, adopted PL relations for IC 1613 Cepheids in the J and K bands. The slope of the relations were adopted from the LMC Cepheids (Persson et al. 2004). They give excellent fits to the observed PL relations in IC 1613.

With the values of the distance moduli of IC 1613 derived in four different bands, providing the large coverage in wavelength from 0.5–2.2 μm, we can compute the reddening and true distance modulus of the galaxy very accurately. Adopting the extinction law of Schlegel et al. (1998) and following the approach we developed in the study of NGC 300 (Gieren et al. 2005a), we fit a straight line to the relation $(m-M)_0 = (m-M)_\lambda - A_\lambda = (m-M)_\lambda - E(B-V)R_\lambda$. The best least-squares fit to this relation yields

$$(m-M)_0 = 24.291 \pm 0.035,$$

$$E(B-V) = 0.090 \pm 0.019.$$

From Figure 6, it is appreciated that the true distance modulus and the total reddening of IC 1613 are indeed very well

TABLE 5

REDDENED AND EXTINCTION-CORRECTED DISTANCE MODULI FOR IC 1613 IN OPTICAL AND NEAR-INFRARED BANDS

Band	V	I	J	K	$E(B-V)$
$m-M$	24.572	24.488	24.385	24.306	...
R_λ	3.24	1.96	0.902	0.367	...
$(m-M)_0$	24.277	24.309	24.302	24.273	0.090

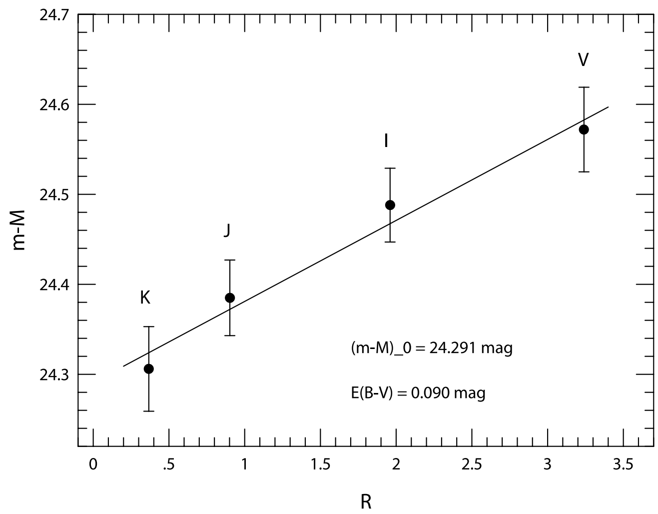

FIG. 6.—Apparent distance moduli to IC 1613 as derived in different photometric bands, plotted against the ratio of total to selective extinction as adopted from the Schlegel et al. reddening law. The intersection and slope of the best fitting line give the true distance modulus and reddening, respectively. The data in this diagram suggest that the Galactic reddening law is a very good approximation for IC 1613 as well.

determined from the available distance moduli in the different photometric bands.

4. DISCUSSION

Here we discuss the various assumptions we made, as well as possible systematic errors that could affect our distance determination of IC 1613. Almost certainly, the largest contribution to our total error budget comes from the current uncertainty of the distance to the LMC. Since this problem has been extensively discussed in the recent literature (e.g., Benedict et al. 2002; Walker 2003), we do not focus on this discussion here. The value of 18.50 mag for the true LMC distance modulus adopted in this paper ensures that our distance results are on the same scale as the results from the *HST* Key Project team (Freedman et al. 2001) and our own previous distance studies in the course of the Araucaria Project (Pietrzyński et al. 2004; Gieren et al. 2004, 2005a).

The adopted fiducial slopes of the J- and K-band Cepheid PL relations from the work of Persson et al. (2004) are based on about 100 LMC Cepheids with periods bracketing those of the IC 1613 Cepheids used in our present study. The Persson et al. infrared PL relations clearly represent the most accurate determination of these relations currently available in the literature. From the recent work of Gieren et al. (2005b), there is evidence that the infrared Cepheid PL relations in the Milky Way agree with the corresponding LMC relations, within the combined 1 σ uncertainties. In Gieren et al. (2005a), we found that the slopes of the Persson et al. PL relations in J and K also provide excellent fits to the Cepheid near-IR data in NGC 300, with its slightly more metal-rich young population than the one in the calibrating LMC (Urbaneja et al. 2005). From the present study of IC 1613, we now see that the slopes of the LMC near-IR PL relations give an excellent fit to the metal-poor population of Cepheids in IC 1613 too. This indicates that, on the one hand, using the Persson et al. LMC PL relations does not introduce any significant systematic error in our current determination of the IC 1613 distance; on the other hand, it strongly suggests that in the near-infrared domain, as in the optical domain, the slope of the Cepheid PL relation is independent of metallicity in the wide range from about -1.0 dex up to solar abundance. This empirical finding is in good agreement with the model predictions of Bono et al. (1999), who have found that both, the zeropoint and the slope of the K-band PL relation depend only marginally on metal abundance. They found that the predicted slope in K is 3.19 ± 0.09 for the LMC and 3.27 ± 0.09 in the SMC, compatible with both the empirical value determined by Persson et al. (2004) for the LMC and with a zero change in the slope of the K-band PL relation when going from LMC (-0.3 dex) metallicity to the SMC (-0.7 dex) metal abundance.

Finally, it is worthwhile to notice that the adoption of the slightly nonlinear PL relations for Cepheids in the LMC, as advocated by Tammann & Reindl 2002, and more recently Ngeow et al. 2005, would practically have no influence on the results presented in this paper. Indeed, as has already been stated in Ngeow et al. (2005), such an effect would introduce a change less than 3% for the derived distance modulus, which is in the order of the one σ error of our current determination. In order to check this out more carefully, we used the Ngeow et al. PL relations in both optical and infrared bands for LMC Cepheids with periods longer than 10 days as fiducial relations and recalculated the distance moduli in the *VIJK* bands. This exercise resulted in revised distance moduli to IC 1613, which in all bands were consistent within one σ with our original results obtained by using the Cepheid PL relations of Udalski (2000) and Persson et al. (2004) for the LMC. The possible nonlinearity of the LMC PL relation, and the associated slight change of its slope for the long-period Cepheids, is therefore not a significant problem in the context of our current distance work. Yet, it will be very important to improve on the slope for the long-period LMC Cepheid PL relation by using very accurate and homogeneous new data. We are currently involved in a project to obtain such new data in the V and I bands.

The sample of Cepheids used for our present distance determination to IC 1613 is relatively large, making our distance result invulnerable to the problem of an inhomogeneous filling of the instability strip which is ideally required in such studies. We suspect that the main reason for the difference of 0.14 mag between our current distance result for IC 1613 and the one obtained by Macri et al. (2001) is the small number of Cepheids available for their study (four), which does not guarantee a homogeneous filling of the instability strip and can cause a relatively large systematic offset of the derived distance modulus from the true value. Therefore, we consider our present result to be consistent with the *HST*-based result of Macri et al. (2001). The location of the Cepheids of our final sample in the CMD in Figure 3 shows that they do indeed cover the instability strip quite homogeneously. Moreover, the period range for the PL solution is very wide and rather uniformly covered with stars-we chose our IR fields in such a way as to optimize the period distribution of the Cepheids in these fields. Applying different cutoff periods to our sample (e.g., $\log P = 0.5$, 0.7, and 1), we always reproduce the zero-point results to within 1 σ. From this we conclude that our choice for the cutoff period does not affect our final results in any significant way.

The most important source of uncertainty while using the optical data *alone* is the interstellar reddening. Our present study shows that most of the reddening to the IC 1613 Cepheids is actually contributed from within the galaxy itself, which explains the overestimation of the distance to IC 1613 in previous studies from optical data that had only used the very small foreground extinction to IC 1613 to make the reddening correction. Using infrared data and in particular K-band photometry, in which the reddening is by an order of magnitude smaller than in the optical bands, the error due to reddening is minimized to a practically insignificant level of about 0.01 mag. From the fact that our new value of $E(B-V)$ yields very consistent distances from the PL relations in all optical and infrared bands, we can also conclude that the extinction law in IC 1613 is not significantly different from the Milky Way law of Schlegel et al. (1998). This is the same conclusion we had already reached in the case of NGC 300 (Gieren et al. 2005a).

Another contribution to the error budget comes from the effect of unresolved companions on the Cepheid magnitudes. The few strongly blended Cepheids in our sample were easily detected from their positions on the multiband PL relations and on the CMD, and were discarded from our further analysis (see § 3.2.). As we extensively discussed in our previous papers (e.g., Gieren et al. 2004, 2005a; Bresolin et al. 2005; Pietrzyński et al. 2004), the blending effect was found to be very small in the cases of NGC 300 and of NGC 6822. In Bresolin et al. (2005) we were able to demonstrate from *HST* ACS images that those Cepheids in NGC 300 that we had identified as strongly blended in the ground-based photometry were indeed the ones with the brightest nearby companions. In that paper it was shown that the effect of unresolved companion stars on the Cepheids that constituted the final sample was less than 2%. Given that IC 1613 is located at less than half the distance of NGC 300 and has a much smaller stellar density, it is reasonable to assume that the effect of blending due to unresolved companion stars on its distance is even smaller than in the case of NGC 300 and does not contribute in a significant way to the systematic uncertainty of our present result.

While it now seems well established that the slopes of the Cepheid PL relations in optical and near-infrared bands do not depend, within our current detection sensitivity, on metallicity over a very broad range of this parameter ($-1 < [\mathrm{Fe/H}] < 0$; see previous discussion), a possible metallicity dependence of their *zero points* is still under discussion (Sakai et al. 2004; Storm et al. 2004; Pietrzyński et al. 2004; Pietrzyński & Gieren 2005). In particular, due to the fact that up to now very few galaxies have been *exhaustively* surveyed for Cepheids in the infrared, it is currently not possible to draw any firm conclusion about the potential variation of the infrared PL relation zero points with metallicity. Soon, once the data for all target galaxies observed in the course of the Araucaria Project have been analyzed, we should be able to put tighter constraints on this open question and, if needed, calibrate the metallicity dependence of PL relation zero points in both optical and infrared domains with high precision.

5. SUMMARY AND CONCLUSIONS

We have measured accurate NIR magnitudes in the J and K bands for 39 Cepheid variables in the Local Group galaxy IC 1613 with well-determined periods and optical (VI) light curves. Mean magnitudes in J and K were derived for these variables using the single-phase approach of Soszyński et al. (2005). After carefully cleaning the Cepheid list from blended objects, Population II variables and overtone pulsators, we have determined accurate PL relations. Fits to these observed relations were made using the slopes of the LMC relations determined by Persson et al. (2004), which gave an excellent representation of the IC 1613 data, providing for the first time solid evidence that the slope of the Cepheid PL relation is independent of metallicity down to the low metallicity of -1.0 dex of the IC 1613 young population in the near-infrared domain too. This is in agreement with the theoretical predictions of Bono et al. (1999). By combining the zero points of the J- and K-band PL relations in our study with the ones derived by Persson et al. for the LMC, we derive relative distance moduli of IC 1613 with respect to the LMC in both bands. Combining these infrared moduli with the distance moduli previously derived by Udalski et al. (2001) in V and I, we determine the total (average) reddening of the Cepheids in IC 1613 and the true distance modulus of this galaxy with an unprecedented accuracy. For the reddening, we find $E(B-V) = 0.090 \pm 0.019$ mag, and for the true distance modulus of IC 1613 from our multiwavelength approach we obtain 24.291 ± 0.035 mag (random error). As in the case of our study of NGC 300 with the same method, we find evidence that there is a significant contribution to the total reddening from dust absorption *intrinsic* to IC 1613, which had been neglected in the previous Cepheid distance work on this galaxy. The excellent fit of the distance moduli to the assumed Galactic extinction law suggests that the interstellar extinction in this small irregular galaxy follows closely the Galactic law.

We show that our derived Cepheid distance is very insensitive to systematic uncertainties caused by the fiducial PL relations used in our fits, possible inhomogeneous filling of the instability strip by our Cepheid sample, and problems with blending of the variables. Any remaining influence of the uncertainty of reddening on our distance result is negligible. All these possible sources of error contribute less to the total systematic uncertainty of our result than the two dominant sources of error, which are the zero points of our *JK* photometry (± 0.03 mag) and the distance to the LMC, which we have *adopted* as 18.50 mag and whose current uncertainty seems in the order of ± 0.10 mag.

Our distance determination for IC 1613 is in reasonable agreement with the previous determination of Macri et al. (2001) from *HST* H-band photometry of four Cepheids, 24.43 ± 0.08 mag. We attribute the 0.14 mag difference mainly to the small number of stars available to Macri et al. in their study. Our new distance determination is also in very good agreement with the very early infrared work of McAlary et al. (1984); these authors had obtained a distance modulus of 24.31 ± 0.12 from H-band data of 10 Cepheids in IC 1613. A change of their assumed reddening of 0.03 mag to our larger value found in this study still produces excellent agreement of their result with ours.

The distance to IC 1613 was also determined by Dolphin et al. (2001) using *HST* data, and employing a number of distance indicators (TRGB, red clump stars, RR Lyrae stars, Cepheids). We note that their Cepheid sample was very small, which can clearly lead to spurious results. Udalski et al. (2001) have observed an order of magnitude larger sample of Cepheids in this galaxy and showed that all these different distance indicators yield consistent distances to this galaxy. Those distance measurements are all in very good agreement with the distance of IC 1613 obtained in this study, assuming the revised reddening of 0.09 mag found in this study and a LMC true distance modulus of 18.5 mag.

As a final conclusion, we have produced in this work a determination of the Cepheid distance to IC 1613 whose random error is of the order of 3%, and the estimated systematic error (excluding the uncertainty of the adopted LMC distance) is of the order of 2%. This accuracy, when combined with distance determinations of similar accuracy we intend to obtain for most of the other galaxies of the Araucaria Project, should enable us to pin down the metallicity dependence of the PL relation zero points in the different optical and near-infrared photometric bands with the 1%–2% accuracy needed to produce a significant improvement in the determination of the Hubble constant from distance determinations to galaxies in the nearby field from their Cepheid populations. This is the approach used in the *HST* Key Project of Freedman et al. (2001), and our work in the Araucaria Project should therefore strongly contribute in the very near future to making the best use of the past work of the Key Project team.

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