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THE ARAUCARIA PROJECT: AN ACCURATE DISTANCE TO THE LOCAL GROUP GALAXY NGC 6822 FROM NEAR-INFRARED PHOTOMETRY OF CEPHEID VARIABLES[1]

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ABSTRACT

We have measured near-infrared magnitudes in the *J* and *K* bands for 56 Cepheid variables in the Local Group galaxy NGC 6822 with well-determined periods and optical light curves in the *V* and *I* bands. Using the template light-curve approach of Soszyński and coworkers, accurate mean magnitudes were obtained from these data, which allowed us to determine with unprecedented accuracy the distance to NGC 6822 from a multiwavelength period-luminosity solution in the *VIJK* bands. From our data, we obtain a distance to NGC 6822 of $(m - M)_0 = 23.312 \pm 0.021$ (random error) mag, with an additional systematic uncertainty of ~3%. This distance value is tied to an assumed LMC distance modulus of 18.50. From our multiwavelength approach, we find for the total (average) reddening to the NGC 6822 Cepheids $E(B - V) = 0.356 \pm 0.013$ mag, which is in excellent agreement with a previous determination by McGonegal and coworkers from near-infrared photometry and implies significant internal reddening of the Cepheids in NGC 6822. Our present, definitive distance determination of NGC 6822 from Cepheids agrees within 2% with the previous distance we had derived from optical photometry alone, but has significantly reduced error bars. Our Cepheid distance to NGC 6822 is in excellent agreement with the recent independent determination of Cioni & Habing from the *I*-band magnitude of the tip of the red giant branch. It also agrees well, within the errors, with the early determination of McGonegal et al. (1983) from random-phase *H*-band photometry of nine Cepheids.

Subject headings: Cepheids — distance scale — galaxies: distances and redshifts — galaxies: individual (NGC 6822) — techniques: photometric

Online material: color figure, machine-readable tables

1. INTRODUCTION

Cepheid variables are the most important distance indicators for calibrating the first rungs of the distance ladder, out to some 30 Mpc. As young stars, Cepheids tend to lie in dusty regions in their spiral or irregular parent galaxies. This implies that distance determinations using Cepheids in the optical spectral range are very sensitive to an accurate knowledge of the total reddening, including the reddening produced inside the parent galaxy itself. Consequently, efforts to use Cepheids as distance indicators in near-infrared passbands started as early as the 1980s with the pioneering work of McGonegal et al. (1982). Perhaps the most important obstacle to deriving truly accurate distances to nearby galaxies from infrared photometry of their Cepheids was the lack of well-calibrated fiducial period-luminosity (PL) relations in the near-infrared *JHK* bands. This long-standing problem was finally solved with the work of Persson et al. (2004), who provided such fiducial PL relations in the Large Magellanic Cloud

[1] Based on observations obtained with the European Southern Observatory (ESO) New Technology Telescope (NTT) for Large Program 171.D-0004, and with the Magellan Telescope of Las Campanas Observatory.

(LMC). Very recently, Gieren et al. (2005b) have also provided well-calibrated Cepheid PL relations in *JHK* for the Milky Way, which are in very good agreement with the corresponding LMC relations when using an improved version of their original infrared surface brightness technique (Fouqué & Gieren 1997; Gieren et al. 1997, 1998) employed for the distance determination of individual Cepheids.

In the Araucaria Project, we have conducted optical (*BVI*) surveys for Cepheid variables from wide-field images for a number of nearby galaxies in the Local Group and in the more distant Sculptor Group. The main goal is to carry out a detailed investigation of the respective dependences on environmental properties of a number of stellar distance indicators, including Cepheid variables, hereby improving the use of these objects as standard candles. While we discover the Cepheids in optical bands in which these stars are easy to find due to their relatively large light amplitudes and characteristic light-curve shapes, the most accurate distance determinations come from near-infrared follow-up photometry of selected subsamples of Cepheids, which allow a dramatic reduction of the systematic uncertainty of the distances due to reddening. Our previous near-infrared work in the Araucaria Project on Cepheids in NGC 300 (Gieren et al. 2005a), IC 1613 (Pietrzyński et al. 2006), and NGC 3109 (Soszyński et al. 2006) has already clearly demonstrated that errors in the adopted reddenings, which often neglect the contribution to the total reddening produced inside the host galaxies, is usually the largest single systematic error in Cepheid distances to galaxies derived from optical photometry alone. Near-infrared follow-up work is a *must* if one wants to push the distance uncertainties down to the 3% level.

In this paper, we present near-infrared photometry in the *J* and *K* bands for 56 Cepheid variables with periods between 124 and 1.7 days, which are scattered across the entire surface of the Local Group irregular galaxy NGC 6822. These variables were previously discovered from optical *VI* images by Pietrzyński et al. (2004, hereafter Paper I). At a galactic latitude of $-18°$, there is substantial foreground reddening to NGC 6822, which implies that not only must any intrinsic contribution to the reddening of the Cepheids be carefully determined for an accurate distance measurement, but that the foreground reddening may not be well determined either. We show that as in our previous work on NGC 300, IC 1613, and NGC 3109, the combination of the new infrared photometry presented here with the previous optical photometry of the Cepheids results in a very accurate determination of the total reddening and of the distance to NGC 6822, which will be extremely useful for the study of the environmental dependences of Cepheids and other stellar distance indicators by comparative studies, and will be the subject of forthcoming papers in our project. Our paper is organized as follows: in § 2 we describe the observations, reduction, and calibrations of our data; in § 3 we present the calibrated near-infrared mean magnitudes of the Cepheids in our selected fields and determine the total reddening and the distance of NGC 6822; and in § 4 we discuss our results and present some conclusions.

2. OBSERVATIONS, DATA REDUCTION, AND CALIBRATION

The near-infrared data presented in this paper were collected with two instruments: Persson's Auxiliary Nasmyth Infrared Camera (PANIC) at the Magellan-Baade telescope at Las Campanas Observatory, and the SOFI camera at the ESO NTT telescope at La Silla. The field of view of the PANIC near-infrared camera is about $2' \times 2'$, and the pixel scale is $0\farcs15$ pixel^{-1}. The SOFI infrared camera was used in its Large Field setup, with a field of view of $4\farcm9 \times 4\farcm9$ and a scale of $0\farcs288$ pixel^{-1}. More details on these instruments can be found on their respective Web pages. We observed a total of eight different PANIC fields and six SOFI fields. The fields are overlapping and cover most of the spatial extent of NGC 6822. The location of the different fields was chosen as to maximize the number of the (relatively few) long-period Cepheids in the fields; with our chosen field coordinates, we were able to obtain infrared photometry for 17 out of the 22 Cepheids with periods longer than 10 days in the Cepheid catalog we presented in Paper I. Figure 1 shows the location of our observed fields in NGC 6822.

Single deep *J* and K_s observations were obtained under good seeing conditions on four different nights at Las Campanas and on two nights at La Silla. On two photometric nights, we observed a large number of photometric standard stars from the United Kingdom Infrared Telescope (UKIRT) system (Hawarden et al. 2001). In order to account for the rapid sky brightness variations in the near-infrared, the observations were performed with a jittering technique. In the K_s 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 at 62 different jittering positions resulted in a total net exposure time of 62 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 jittering positions, which resulted in a total net exposure of about 17 minutes for any given field.

Sky subtraction was performed by using a two-step process employing the masking of stars with the XDIMSUM IRAF package in an analogous manner, as described in Pietrzyński & Gieren (2002).[2] 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. (2002). 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 this way and 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 SOFI 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 science fields. The standard stars were chosen to have colors bracketing the colors of the Cepheids in NGC 6822. 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 on every night. The accuracy of the zero points of our photometry was determined to be ± 0.02 mag. The data obtained with the PANIC camera were transformed to the standard system using stars in common with the SOFI fields.

Since our science fields overlap (see Fig. 1), we were able to perform an internal check on our photometry by comparing the

[2] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the NSF.

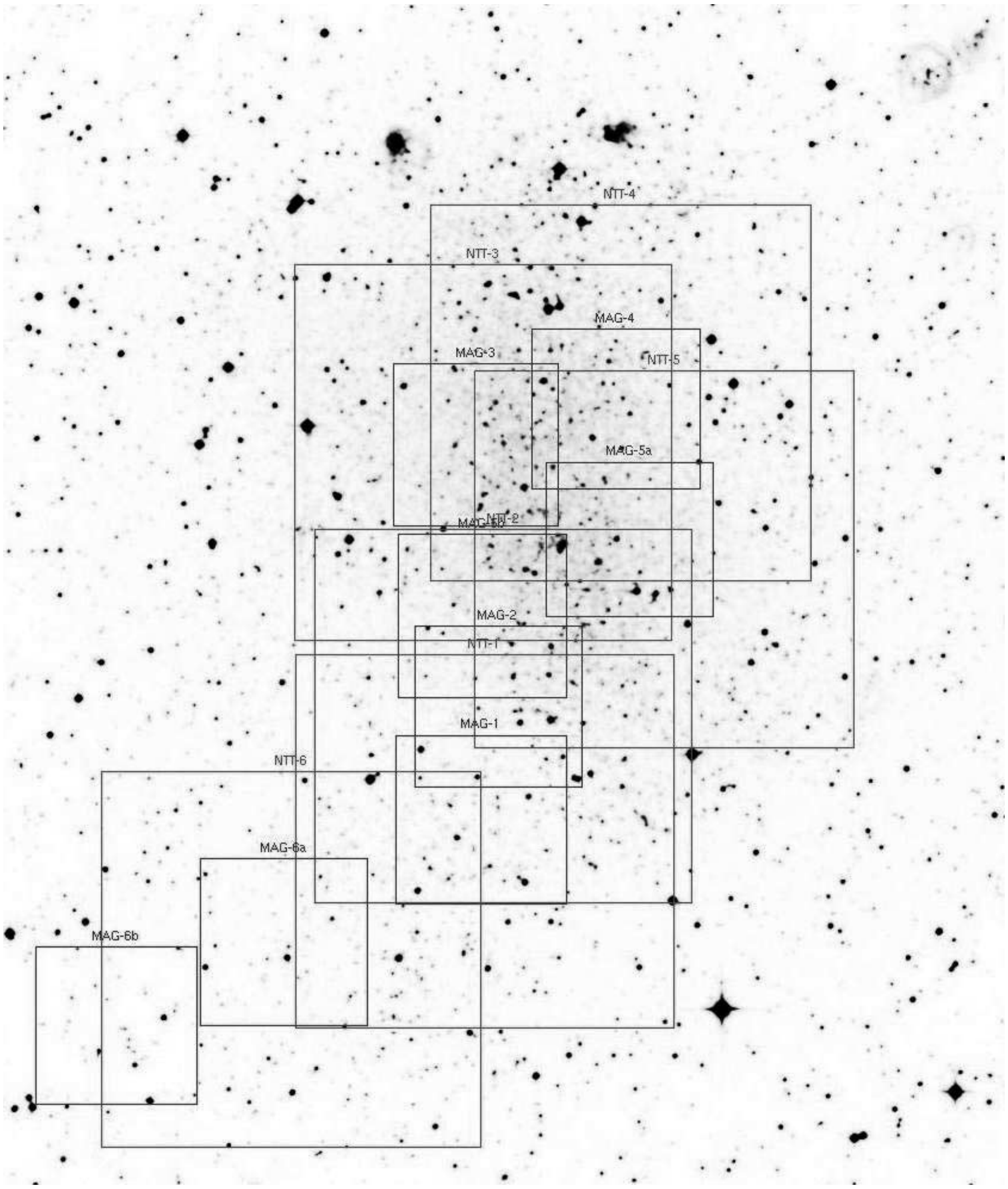

FIG. 1.—Location of the observed fields in NGC 6822 on the DSS blue plate. We observed six NTT SOFI fields and eight Magellan PANIC fields (see text). The fields cover most of the spatial extent of the galaxy and contain 17 Cepheid variables with periods in excess of 10 days. [*See the electronic edition of the Journal for a color version of this figure*.]

magnitudes of stars located in the common regions. In all cases, the independently calibrated magnitudes agree within 0.02–0.03 mag in both *J* and *K* filters. For the relatively bright stars in our fields, the magnitudes can be compared to the corresponding Two Micron All Sky Survey (2MASS) magnitudes. Figure 2 presents such a comparison in *J* and *K* for the common bright stars. Before calculating the differences between our own and the 2MASS photometry, we transformed our photometry, which had been calibrated to the UKIRT system, to the 2MASS system using the equations provided by Carpenter (2001). Figure 2 suggests that our magnitudes in both *J* and *K* are about 0.03 mag brighter than the corresponding 2MASS magnitudes, but given the rather large scatter in the 2MASS data for the fainter stars, this offset does not seem significant. In any case, the comparison confirms our conclusion that our photometric zero points in *J* and *K* are accurate to at least 0.03 mag.

The pixel positions of the stars were transformed to the equatorial coordinate system using the Digitized 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 $0\overset{''}{.}3$.

3. RESULTS

3.1. *The Cepheid Mean J and K Magnitudes*

Altogether, our observed fields in NGC 6822 contain 56 Cepheids bright enough to measure their near-infrared magnitudes. As we mentioned before, we chose our fields in such a

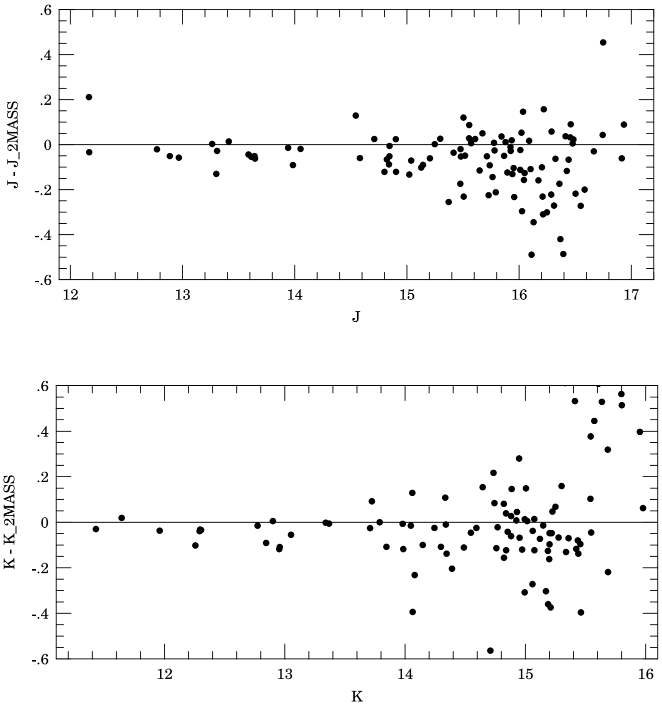

FIG. 2.—Comparison of our NGC 6822 near-infrared photometry with 2MASS data for common stars. The brightest common stars with reasonably high signal-to-noise ratios in the 2MASS photometry suggest a slight systematic offset of −0.03 mag in both bands in the sense that our J and K magnitudes are on average brighter by this amount. The deviation is likely to be not significant.

way as to maximize the number of long-period Cepheids in them, and we obtained photometry for 17 of the 22 Cepheids with periods longer than 10 days in our previous catalog (Paper I). The faintest Cepheids for which we could measure relatively accurate J and K magnitudes have periods around 4–5 days.

In Table 1 we present the journal of individual observations of these 56 Cepheid variables. The identifications are as in the catalog in Paper I. Nearly all of these objects have observations at more than one pulsation phase, and some of them have JK observations at four different phases in their light curves. The mean magnitudes of the Cepheids were derived from each individual single-phase measurement from the template light-curve method developed by our group (Soszyński et al. 2005), which uses the V- and I-band phases of the individual near-IR observations, and the light-curve amplitudes in V and I, to calculate the differences of the individual single-phase magnitudes from the mean magnitudes in J and K. For a detailed description of the technique, the reader is referred to Soszyński et al. (2005), who demonstrated that the mean K and J magnitudes of Cepheids can be derived from just one single-phase infrared observation with an accuracy of 0.02–0.03 mag, provided that high-quality optical light curves and periods are available for the variables, which is clearly the case in this study. Obviously, the availability of more than one near-IR observation of a Cepheid increases the accuracy of the determination of its mean near-IR magnitude because one can average the various independent determinations. In Table 2 we present the final intensity-mean JK magnitudes of our Cepheid sample with their estimated uncertainties, which were determined from the photometric accuracies of the individual random-phase measurements of a given variable and from the additional uncertainty introduced in the calculation of the mean magnitudes from the template method. In all cases where more than one near-IR observation for a given Cepheid was available, the independent determinations of its mean magnitude agreed very well, typically within 1%–3%, reconfirming the quality of our present near-infrared photometry as well as the accuracy of our previous VI light curves and periods given in Paper I.

3.2. *Near-Infrared Period-Luminosity Relations and Distance Determination*

In Figure 3 we show the J- and K-band Cepheid PL relations in NGC 6822 obtained from the mean magnitudes and periods in Table 2. Our sample defines the PL relations exceedingly well. We have adopted a period cutoff of 4.8 days in order to avoid any significant contamination of our sample with possible overtone pulsators, which may appear in increasing numbers at shorter periods and which could bias the distance determination. Another reason to exclude stars with periods less than 4.8 days is the increasingly larger random errors in their photometry due to the increasing faintness of these objects. For the fits to a line, we decided to exclude four objects, which are identified by open circles in Figure 3. As in our previous discussion of optical work in Paper I, we exclude the one Cepheid with a period longer than 100 days, for the reasons given in that paper. The other three objects (variables cep025, cep028, and cep052) are excluded on the basis of their large deviations from the mean J- and K-band PL relations defined by the remaining 33 stars. The same three Cepheids deviate consistently in both bands, in the sense that their magnitudes are too bright for their periods, which suggests that these objects are blended with relatively bright nearby stars that are not resolved in our images. One of these objects, cep028 at $\log P = 0.858$, is also clearly overluminous in the optical (VI) PL relations, whereas cep025 and cep052 lie close to the ridge lines in the V- and I-band PL relations. This could indicate that for these two stars, the unresolved companions are very red and their contribution to the measured fluxes of the Cepheids is only strongly noted in the near-infrared. For the adopted sample of 33 Cepheids, the dispersions of the PL relations in both J and K around the ridge lines are so small that they basically reflect the intrinsic dispersions caused by the finite width of the Cepheid instability strip; this is suggested by a comparison of the present relations to the exceedingly well determined near-infrared Cepheid PL relations in the LMC of Persson et al. (2004). Finally, we also note that a possible contamination of our sample with first overtone pulsators is very unlikely, given that the shortest periods of about 5 days in our sample are too long for first-overtone Cepheids.

Least-squares fits to a line to our data for the adopted 33 Cepheids in Figure 3 yield slopes of the PL relations of -3.28 ± 0.04 in K and -3.23 ± 0.05 in J, respectively. These values agree very well with the slopes for the Cepheid PL relations in the LMC, which are -3.261 in K and -3.153 in J (Persson et al. 2004), suggesting that the slope of the PL relation in the near-infrared domain remains unchanged when going from the LMC to the slightly more metal-poor NGC 6822 Cepheids. This result is in line with the fact that the LMC slopes also yield very good fits to the Cepheids in IC 1613, which are even more metal-poor than the Cepheids in NGC 6822 (Pietrzyński et al. 2006). Following the procedure used in our previous papers, we adopt the LMC slopes of Persson et al. (2004) in our fits. This yields the following PL relations for NGC 6822:

$$J = -3.153 \log P + (21.425 \pm 0.025)$$
$$K = -3.261 \log P + (20.999 \pm 0.021).$$

These relations are shown in Figure 3. It can be seen that they fit the data extremely well. Before calculating the relative distance

TABLE 1

Journal of the Individual *J*- and *K*-band Observations of NGC 6822 Cepheids

ID	HJD (*J* Observations)	*J* (mag)	σ (mag)	HJD (*K* Observations)	*K* (mag)	σ (mag)
cep001	3215.771560	15.515	0.026	3215.716360	14.990	0.010
	3226.567980	15.517	0.009	3226.502680	14.932	0.021
	3250.648500	15.543	0.008	3250.664120	15.029	0.009
cep002	3215.619160	15.555	0.005	3215.564180	14.948	0.005
	3215.692830	15.544	0.004	3215.636120	14.947	0.005
	3250.545020	15.347	0.005	3250.571990	14.905	0.009
cep003	3215.771560	16.396	0.042	3215.716360	15.892	0.021
	3250.724570	16.526	0.009	3250.694500	15.809	0.018
cep004	3215.619160	16.597	0.012	3215.564180	15.941	0.008
	3215.692830	16.639	0.010	3215.636120	15.841	0.023
	3250.633530	16.581	0.006	3250.602610	15.917	0.012
cep007	3215.771560	16.787	0.013	3215.716360	16.120	0.016
	3226.567980	16.750	0.014	3226.502680	16.327	0.021
	3226.664610	16.673	0.014	3226.603750	16.215	0.028
	3250.648500	17.014	0.009	3250.664120	16.309	0.015
cep008	3215.771560	16.577	0.015	3215.716360	16.073	0.025
	3226.567980	16.717	0.015	3226.502680	16.135	0.015
	3226.664610	16.655	0.014	3226.603750	16.178	0.018
	3250.724570	16.805	0.007	3250.694500	16.142	0.014
cep010	3215.619160	17.364	0.009	3215.564180	16.726	0.009
	3215.692830	17.379	0.010	3215.636120	16.711	0.011
	3250.545020	17.238	0.009	3250.571990	16.650	0.016
cep011	3215.771560	17.410	0.014	3215.716360	16.813	0.018
	3250.724570	17.630	0.015	3250.694500	16.929	0.025
cep012	3215.619160	17.717	0.012	3215.564180	17.075	0.014
	3215.692830	17.741	0.018	3215.636120	17.097	0.016
cep013	3251.560460	17.212	0.031	3251.528590	16.790	0.031
cep014	3215.619160	17.668	0.017	3215.564180	17.020	0.019
	3215.692830	17.715	0.014	3215.636120	17.067	0.017
cep015	3215.619160	17.631	0.023	3215.564180	17.150	0.027
	3215.692830	17.631	0.018	3215.636120	17.138	0.015
	3226.664610	17.316	0.015	3226.603750	16.895	0.023
cep016	3215.619160	17.658	0.015	3215.564180	17.074	0.012
cep017	3215.771560	17.421	0.021	3215.716360	16.908	0.030
	3251.560460	17.621	0.016	3251.528590	17.005	0.024
cep018	3215.619160	17.925	0.016	3215.564180	17.371	0.021
	3215.692830	18.008	0.016	3215.636120	17.431	0.023
	3250.633530	17.631	0.016	3250.602610	17.103	0.020
	3299.592960	17.801	0.026	3299.551310	17.445	0.018
cep019	3215.692830	17.913	0.016	3215.636120	17.276	0.021
	3215.771560	18.151	0.020	3215.716360	17.598	0.026
	3226.567980	17.874	0.031	3226.502680	17.454	0.042
	3226.664610	17.977	0.020	3226.603750	17.329	0.025
	3251.560460	17.846	0.021	3251.528590	17.271	0.030
cep022	3215.692830	18.268	0.037	3215.636120	17.862	0.052
cep023	3215.619160	18.266	0.018	3215.564180	17.822	0.025
cep024	3226.567980	17.594	0.021	3226.502680	17.027	0.032
	3226.664610	17.678	0.020	3226.603750	17.064	0.042
	3251.560460	18.128	0.018	3251.528590	17.738	0.037
cep025	3215.771560	17.915	0.029	3215.716360	17.047	0.016
	3250.648500	17.877	0.015	3250.664120	16.933	0.024
cep026	3215.619160	18.304	0.016	3215.564180	17.765	0.022
	3215.692830	18.239	0.016	3215.636120	17.797	0.026
	3250.545020	18.188	0.020	3250.571990	17.662	0.044
cep027	3215.619160	18.353	0.027	3215.564180	17.847	0.030
	3215.692830	18.336	0.025	3215.636120	17.859	0.030
cep028	3215.619160	17.353	0.012	3215.564180	16.591	0.013
	3215.692830	17.351	0.011	3215.636120	16.675	0.016
cep029	3215.619160	18.710	0.025	3215.564180	18.010	0.031
	3215.692830	18.679	0.025	3215.636120	18.000	0.034
	3250.633530	18.652	0.023	3250.602610	18.284	0.048
	3250.545020	18.744	0.027	3250.571990	18.237	0.044
cep030	3215.771560	19.090	0.051	3215.716360	18.519	0.047
	3250.724570	19.041	0.065	3250.694500	18.297	0.056

TABLE 1—*Continued*

ID	HJD (*J* Observations)	*J* (mag)	(mag)	HJD (*K* Observations)	*K* (mag)	(mag)
cep031	3215.771560	18.872	0.030	3215.716360	18.256	0.041
	3250.724570	19.042	0.028	3250.694500	18.386	0.044
cep033	3215.771560	18.367	0.034	3215.716360	17.838	0.051
	3299.592960	18.761	0.027	3299.551310	18.392	0.036
cep034	3215.692830	18.653	0.029	3215.636120	18.098	0.036
	3215.771560	18.496	0.023	3215.716360	17.976	0.031
cep037	3250.724570	18.985	0.036	3250.694500	18.289	0.047
cep041	3215.692830	19.329	0.047	3215.636120	18.599	0.046
	3215.771560	19.340	0.050	3215.716360	18.622	0.047
	3299.592960	19.014	0.043	3299.551310	18.513	0.044
cep043	3250.648500	18.858	0.021	3250.664120	18.410	0.042
cep048	3250.724570	19.459	0.035	3250.694500	18.984	0.069
cep051	3215.619160	19.032	0.033	3215.564180	18.540	0.050
	3215.692830	18.984	0.033	3215.636120	18.566	0.041
	3250.633530	18.875	0.019	3250.602610	18.549	0.044
cep052	3215.771560	17.435	0.024	3215.716360	16.576	0.014
cep056	3215.771560	19.536	0.068	3215.716360	19.015	0.088
cep057	3215.619160	19.159	0.031	3215.564180	18.855	0.053
cep058	3215.692830	19.181	0.062	3215.636120	18.596	0.055
	3215.771560	19.234	0.060	3215.716360	18.620	0.054
	3251.560460	19.248	0.030	3251.528590	18.803	0.056
cep061	3215.771560	18.687	0.037	3215.716360	17.949	0.045
cep063	3215.771560	18.605	0.031	3215.716360	18.061	0.044
	3250.724570	18.823	0.026	3250.694500	18.178	0.043
cep064	3215.619160	18.852	0.028	3215.564180	18.390	0.038
	3215.692830	19.016	0.034	3215.636120	18.356	0.033
cep067	3215.619160	19.490	0.038	3215.564180	19.024	0.059
cep068	3215.619160	18.627	0.035	3215.564180	17.918	0.085
	3215.692830	18.668	0.029	3215.636120	17.955	0.039
	3226.664610	18.460	0.041	3226.603750	17.929	0.053
cep069	3215.692830	19.176	0.043	3215.636120	19.171	0.070
cep070	3215.692830	19.551	0.070	3215.636120	18.842	0.096
cep073	3215.619160	20.156	0.129	3215.564180	19.485	0.149
cep075	3226.567980	17.322	0.019	3226.502680	15.978	0.013
cep076	3215.692830	18.350	0.035	3215.636120	17.897	0.070
	3299.592960	18.586	0.062	3299.551310	18.333	0.072
cep077	3215.619160	18.972	0.053	3215.564180	18.300	0.067
	3215.692830	18.965	0.041	3215.636120	18.420	0.068
	3250.633530	18.958	0.031	3250.602610	18.589	0.047
cep078	3250.633530	19.084	0.030	3250.602610	18.727	0.062
	3299.592960	19.090	0.032	3299.551310	18.870	0.043
cep083	3215.619160	19.311	0.046	3215.564180	18.454	0.058
cep097	3215.619160	19.412	0.041	3215.564180	19.117	0.063
	3215.692830	19.497	0.042	3215.636120	18.972	0.054
	3250.633530	19.361	0.023	3250.602610	18.889	0.062
	3250.545020	19.319	0.025	3250.571990	19.009	0.067
cep099	3250.545020	19.847	0.038	3250.571990	19.679	0.108
cep101	3215.619160	18.536	0.028	3215.564180	17.608	0.021
	3215.692830	18.505	0.028	3215.636120	17.576	0.020
cep103	3215.692830	19.401	0.058	3215.636120	18.401	0.054
cep113	3215.619160	19.074	0.032	3215.564180	18.595	0.042
cep116	3215.619160	18.980	0.039	3215.564180	18.220	0.040
	3215.692830	18.982	0.037	3215.636120	18.193	0.037

Note.—Table 1 is also available in machine-readable form in the electronic edition of the *Astrophysical Journal*.

of NGC 6822 with respect to the LMC from the zero points in these relations, we need to convert our zero-point magnitudes, which are calibrated to the UKIRT system, to the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) system on which the corresponding LMC zero points were calibrated (Persson et al. 2004). According to Hawarden et al. (2001), there are only zero-point offsets between the UKIRT and NICMOS systems (e.g., no color dependences) 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 18.50 as in our previous work in the Araucaria Project, we derive distance moduli for NGC 6822 of 23.586 mag in the *J* band and 23.463 in the *K* band. Values for the distance modulus of 24.458 in *V* and 24.025 in *I* were found in our previous optical work in Paper I.

As in our previous papers in this series (Gieren et al. 2005a; Pietrzyński et al. 2006), we adopt the extinction law of Schlegel

TABLE 2

Intensity-mean J and K Magnitudes for 56 Cepheid Variables in NGC 6822

ID	log P (days)	$\langle J \rangle$ (mag)	J (mag)	$\langle K \rangle$ (mag)	K (mag)
cep001	2.093	15.445	0.030	14.964	0.029
cep002	1.815	15.475	0.025	14.946	0.026
cep003	1.570	16.277	0.039	15.678	0.032
cep004	1.540	16.579	0.027	15.963	0.030
cep007	1.485	16.695	0.028	16.099	0.032
cep008	1.466	16.740	0.028	16.219	0.031
cep010	1.301	17.376	0.027	16.802	0.028
cep011	1.299	17.489	0.029	16.812	0.033
cep012	1.292	17.592	0.029	17.008	0.029
cep013	1.286	17.344	0.040	16.845	0.040
cep014	1.264	17.495	0.029	16.927	0.031
cep015	1.240	17.435	0.031	17.020	0.033
cep016	1.229	17.795	0.029	17.184	0.028
cep017	1.226	17.579	0.031	17.047	0.037
cep018	1.141	17.768	0.031	17.254	0.032
cep019	1.048	17.884	0.033	17.355	0.039
cep022	1.012	18.234	0.045	17.901	0.053
cep023	0.981	18.368	0.031	17.892	0.035
cep024	0.972	17.896	0.032	17.342	0.045
cep025	0.951	17.854	0.034	16.987	0.032
cep026	0.928	18.345	0.030	17.802	0.041
cep027	0.924	18.429	0.036	17.921	0.039
cep028	0.858	17.380	0.028	16.680	0.029
cep029	0.852	18.711	0.035	18.099	0.047
cep030	0.838	18.968	0.064	18.387	0.057
cep031	0.837	18.915	0.038	18.355	0.049
cep033	0.828	18.521	0.040	18.090	0.051
cep034	0.816	18.672	0.036	18.094	0.042
cep037	0.788	18.898	0.044	18.274	0.053
cep041	0.776	19.109	0.053	18.532	0.052
cep043	0.752	18.991	0.033	18.483	0.049
cep048	0.714	19.443	0.043	18.912	0.073
cep051	0.708	19.071	0.038	18.585	0.052
cep052	0.707	17.492	0.035	16.703	0.029
cep056	0.689	19.646	0.072	19.047	0.091
cep057	0.684	19.281	0.040	18.863	0.059
cep058	0.671	19.233	0.058	18.672	0.060
cep061	0.658	18.821	0.045	18.028	0.051
cep063	0.648	18.698	0.038	18.140	0.050
cep064	0.639	19.060	0.040	18.445	0.043
cep067	0.627	19.499	0.045	19.079	0.064
cep068	0.626	18.588	0.043	17.967	0.067
cep069	0.625	19.355	0.050	19.294	0.074
cep070	0.614	19.435	0.074	18.665	0.099
cep073	0.601	20.248	0.131	19.435	0.151
cep075	0.591	17.233	0.031	15.986	0.028
cep076	0.578	18.515	0.056	18.155	0.075
cep077	0.577	19.062	0.049	18.505	0.066
cep078	0.570	19.171	0.040	18.782	0.059
cep083	0.554	19.418	0.052	18.564	0.063
cep097	0.455	19.368	0.042	18.952	0.067
cep099	0.426	20.010	0.045	19.709	0.111
cep101	0.414	18.535	0.038	17.639	0.032
cep103	0.405	19.261	0.063	18.349	0.060
cep113	0.316	19.119	0.041	18.605	0.049
cep116	0.233	19.047	0.045	18.239	0.046

Note.—Table 2 is also available in machine-readable form in the electronic edition of the *Astrophysical Journal*.

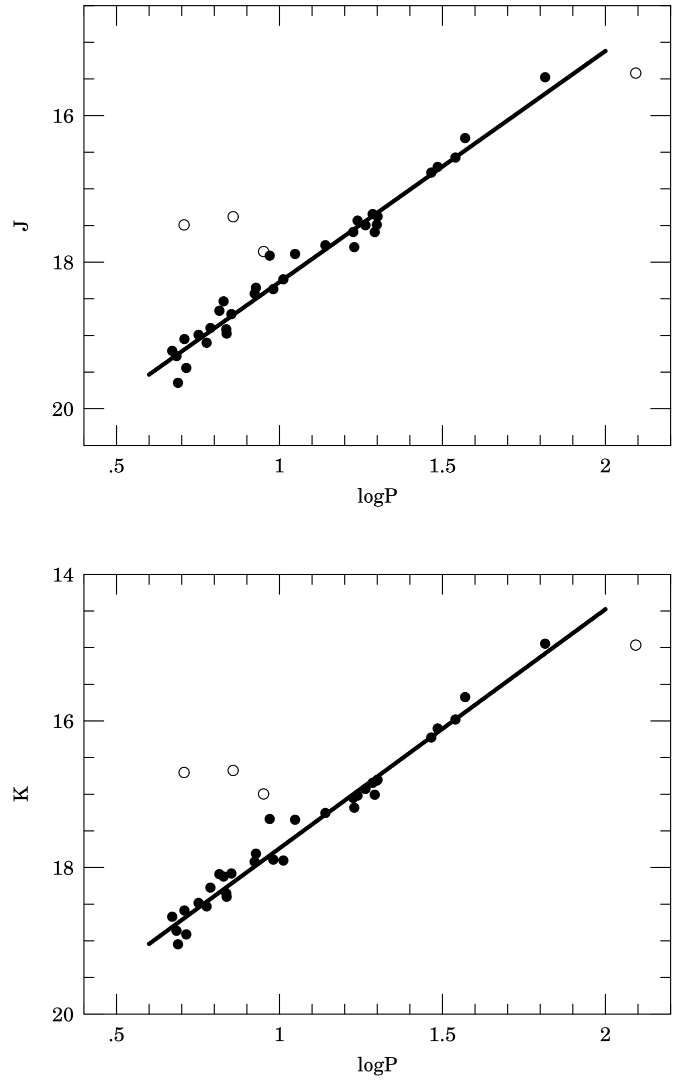

Fig. 3.—Cepheid PL relations for NGC 6822 in the J (*top panel*) and K (*bottom panel*) bands. We have excluded the four objects indicated by open circles in these figures in the distance solutions, for the reasons given in the text. We have also omitted all variables with periods shorter than our adopted cutoff period of 4.8 days (see text).

et al. (1998) and 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 for the reddening and the true distance modulus of NGC 6822 the following values:

$$(m-M)_0 = 23.312 \pm 0.021$$

$$E(B-V) = 0.356 \pm 0.013.$$

In Table 3 we give the adopted values of R_λ and the unreddened distance moduli in each band, which are obtained with

TABLE 3

Reddened and Absorption-corrected Distance Moduli for NGC 6822 in Optical and Near-Infrared Bands

Band	V	I	J	K	$E(B-V)$
$m-M$	24.458	24.025	23.586	23.463	. . .
R_λ	3.24	1.96	0.902	0.367	. . .
$(m-M)_0$	23.304	23.327	23.264	23.332	0.356

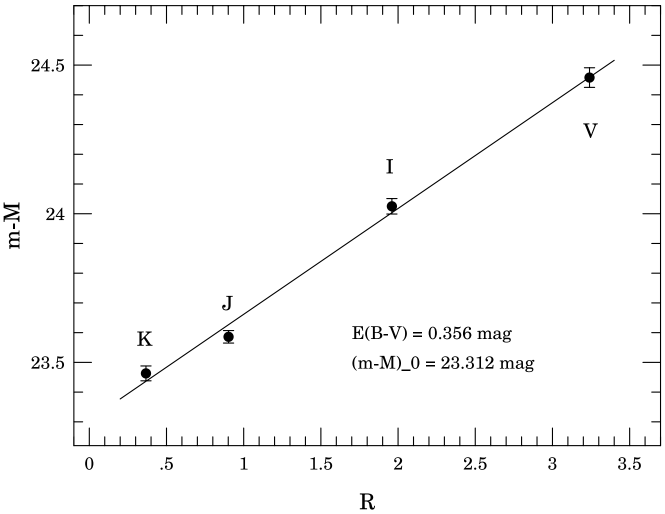

FIG. 4.—Apparent distance moduli to NGC 6822 as derived in different photometric bands, plotted against the ratio of total to selective extinction as adopted from the Schlegel et al. (1998) reddening law. The intersection and slope of the best-fitting line give the true distance modulus and reddening, respectively. The data in this diagram suggest that the galactic reddening law is a very good approximation for NGC 6822 as well.

the reddening determined in our multiwavelength approach. The agreement between the unreddened distance moduli in each band is excellent. In Figure 4 we show the apparent distance moduli in *VIJK* as a function of R_λ, and the best fit to the data; it is appreciated that the total reddening and the true distance modulus of NGC 6822 are indeed very well determined from this fit. Comparison of our reddening value to the foreground reddening to NGC 6822 of 0.236 demonstrates that there is indeed a significant contribution to the total reddening of the Cepheids that is produced by dust extinction in the galaxy itself, in agreement with what we found for NGC 300 and IC 1613 in the earlier papers in this series. In the case of NGC 6822, our data suggest that the reddening produced internal to the galaxy is 0.12 mag.

4. DISCUSSION AND CONCLUSIONS

Here we discuss the various assumptions that we make and possible systematic errors that could affect our distance determination of NGC 6822.

The potentially largest single systematic uncertainty on the derived distance modulus of NGC 6822 comes from the current uncertainty on the adopted distance modulus for the LMC. This problem has been extensively discussed in recent literature (e.g., Benedict et al. 2002), and we do not add to this discussion here. We just note that our adopted value of 18.50 for the LMC distance is in agreement with the value adopted by the Key Project of Freedman et al. (2001), and since all the Cepheid distances obtained for the different target galaxies in our project are tied to the same LMC distance, the *relative* distances between our target galaxies are not affected.

In a recent paper that presented our near-infrared Cepheid photometry for another Local Group irregular galaxy, IC 1613 (Pietrzyński et al. 2006), we discussed in some detail why our distance results derived from our current multiwavelength approach are little affected by the choice of the fiducial PL relations in the LMC. The Persson et al. (2004) *JK* Cepheid PL relations we have used in this work are clearly extremely well established, at least for periods longer than 10 days. The Persson et al. sample, however, does not contain many Cepheids with shorter periods, so a possible break in the PL relation at 10 days as advocated by Kanbur & Ngeow (2004) and Ngeow et al. (2005) would not be easily detected. Our previous results in the Araucaria Project on NGC 300, whose Cepheids have on average LMC metallicity (Urbaneja et al. 2005), and on the much more metal-poor IC 1613 galaxy (Pietrzyński et al. 2006), have shown that within very small uncertainties the PL relation in *J* and *K* seems universal in the metallicity range from about −0.3 to −1.0 dex. Any concerns about the universality of the PL relation, as advocated by Sandage et al. (2004) and Ngeow & Kanbur (2004), seem to refer to the metallicity range between solar and LMC abundance. While the former studies find a steeper slope for the Milky Way PL relation than for the LMC, in agreement with the work of Fouqué et al. (2003) from the infrared surface brightness technique, there is now recent evidence that the Milky Way PL relation actually agrees in slope with the LMC relation when a systematic error in the surface brightness technique is corrected (Gieren et al. 2005b). Clearly, the question of the universality of the PL relation, particularly in the range between solar and LMC metallicity, has to be further investigated in order to obtain a clear-cut and convincing result, and this is one of the main purposes of our project. Regarding the possible break of the PL relation at 10 days discussed by Sandage et al. (2004) and more recently by Ngeow et al. (2005), we clearly have not seen such an effect on the data for any of the galaxies we have so far studied in the Araucaria Project. The effect, if real, must be very subtle, and indeed Ngeow et al. (2005) have estimated that its effect on distance determinations with the PL relation should be less than 3% and therefore not a cause of serious concern as long as we do not strive for distance accuracies of 1%, which seem out of reach for nongeometrical methods at the present time.

As in the previous papers in this series on NGC 300 (Gieren et al. 2005a), IC 1613 (Pietrzyński et al. 2006), and very recently NGC 3109 (Soszyński et al. 2006), we are able to measure very accurate mean *JK* magnitudes for a very sizable sample of Cepheids in NGC 6822 that cover a broad range of periods, and establish a final sample of variables that is very unlikely to be affected by the presence of overtone pulsators or heavily blended stars, which could seriously bias our determination of the zero points of the PL relations in the *J* and *K* bands. Regarding the possible effect of blending, viz., of the effect of nearby companion stars to the Cepheids that are not resolved in our photometry, we have shown in the case of the more distant NGC 300 from *Hubble Space Telescope* images that the effect on the distance determination does not exceed 2% (Bresolin et al. 2005). In the present case of NGC 6822 the effect is expected to be smaller because the galaxy is about 4 times closer than NGC 300 and has a smaller average stellar density. In addition, heavily blended Cepheids can be rather easily recognized and eliminated from the sample used for the distance determination (as we did in this study) from their observed positions on the PL planes *if* the observational scatter is low, as a consequence of using photometric data of high quality. This is certainly the case for the present data, and we already remarked before that the dispersion in Figure 3 is so small that it approaches the *intrinsic* dispersion expected from the finite width of the Cepheid instability strip, with only a small additional contribution from photometric errors that is mostly visible at the shortest periods in Figure 3. This eliminates any concern that blending could bias our present distance determination by more than 2%. Also, the relatively large size of our sample eliminates concerns about the effect of incomplete filling of the instability strip (see also the discussion in Pietrzyński et al. [2006], and our previous paper presenting the optical photometry of the NGC 6822 Cepheids [Paper I]).

As we have shown in our previous papers in this series, the most important source of uncertainty in Cepheid-based distance determinations of nearby, resolved galaxies from optical photometric data alone is the interstellar reddening. In both NGC 300 and IC 1613 we found from our infrared studies that there is a very significant *intrinsic* contribution to the reddening, in addition to the galactic foreground reddening in the directions to these galaxies. The most important gain in extending the Cepheid observations to the infrared is the possibility of determining the total reddening very accurately, as again demonstrated in this paper, for the case of NGC 6822. Our definitive distance determination of NGC 6822 from Cepheids presented in this paper agrees very closely with our previous, preliminary result from *VI* photometry presented in Paper I, because we happened to use the correct reddening value in that paper. The agreement of the reddening of NGC 6822 derived from Cepheid *H*-band photometry by McGonegal et al. (1983) with our present value from *VIJK* photometry of Cepheids confirms the excellent pioneering infrared work done by these authors more than 20 years ago.

As a result of this discussion and those presented in our previous papers in this series, we conclude that the total effect of systematic errors due to the fiducial PL relations we use, possible incomplete filling of the instability strip and contamination of our Cepheid samples with overtone pulsators, and blending with unresolved companion stars in our photometry does not exceed 3%. The systematic uncertainty of our adopted photometric zero points, which propagates directly into the distance determination, is of the order of 0.03 mag, or $\pm 1.5\%$, in all bands. Random errors due to photometric noise are clearly less important in the present case and do not contribute significantly to the error budget. We therefore conclude that the present distance determination to NGC 6822 from our combined optical and near-infrared photometry of Cepheids in this galaxy is accurate, including systematics, to about $\pm 3\%$. We stress, however, that this value does not include the contribution from the current uncertainty of the LMC distance, which could be as large as 10%. For the immediate purposes of the Araucaria Project, however, *relative* distances are essential, and we now have another galaxy whose distance relative to the LMC appears to be determined with the same high accuracy of about $\pm 3\%$ as for the other galaxies for which we have used Cepheid infrared photometry for distance determination, viz., NGC 300, IC 1613, and NGC 3109.

Finally, we note that our present distance result of 23.31 ± 0.02 (random) $\pm\sim$ 0.06 (systematic) based on Cepheid variables agrees very well with the recent distance determination of Cioni & Habing (2005), who obtained a true distance modulus of 23.34 ± 0.12 mag for NGC 6822 from the observed *I*-band magnitude of the tip of the red giant branch. It also agrees reasonably well with the former Cepheid near-infrared distance to NGC 6822 of $(m - M)_0 = 23.47 \pm 0.11$ derived by McGonegal et al. (1983) using the same reddening as the one we found in this paper, from random-phase *H*-band photometry of nine Cepheids, which was not corrected to the mean magnitudes as in our present work. This fact alone, combined with the small number of Cepheids they used in their PL solution, may easily explain the 0.16 mag deviation of their value from ours.

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