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THE ARAUCARIA PROJECT: THE DISTANCE TO THE LOCAL GROUP GALAXY WLM FROM CEPHEID VARIABLES DISCOVERED IN A WIDE-FIELD IMAGING SURVEY[1]

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ABSTRACT

We have conducted an extensive wide-field imaging survey for Cepheid variables in the Local Group irregular galaxy WLM. From data obtained on 101 nights, we have discovered 60 Cepheids, which include 14 of the 15 Cepheid variables previously detected by Sandage and Carlson. Our Cepheid survey in WLM should be practically complete down to a period of 3 days. Importantly, we have found for the first time a long-period Cepheid ($P = 54.2$ days) in this galaxy, alleviating the problem that WLM with its many blue, massive stars does not contain Cepheids with periods longer than about 10 days. Our data define tight period-luminosity (PL) relations in V, I, and the reddening-free Wesenheit magnitude W_I, which are all extremely well fit by the corresponding slopes of the LMC Cepheid PL relation, suggesting no change of the PL relation slope down to a Cepheid metal abundance of about -1.0 dex, in agreement with other recent studies. We derive a true distance modulus to WLM of 25.144 ± 0.03 (random) ± 0.07 (systematic) mag from our data, in good agreement with the earlier 24.92 ± 0.21 mag determination of Lee, Freedman, and Madore from Cepheid variables. The quoted value of the systematic uncertainty does not include the contribution from the LMC distance, which we have assumed to be 18.50 mag, as in the previous papers in our project.

Key words: Cepheids — distance scale — galaxies: distances and redshifts — galaxies: individual (WLM) — galaxies: stellar content

Online material: machine-readable tables

1. INTRODUCTION

In our ongoing Araucaria Project, we are improving on the usefulness of a number of stellar distance indicators by determining their environmental dependences from a study of these objects in nearby galaxies with largely different environmental parameters. We have described our approach and motivations to improve the local calibration of the extragalactic distance scale in a number of previous papers (Pietrzynski et al. 2002a; Gieren et al. 2005c). Among the known stellar methods of distance determination Cepheid variables continue to be the most powerful standard candles to determine the distances to galaxies out to about 10 Mpc, especially when they are used in the near-infrared

[1] Based on observations obtained with the 1.3 m telescope at the Las Campanas Observatory.

domain, where the problems with dust absorption, particularly intrinsic to the host galaxies, can be minimized (Gieren et al. 2005a, 2006; Pietrzynski et al. 2006a; Soszynski et al. 2006). For this reason, we have made a considerable effort to discover large samples of Cepheid variables in the target galaxies of the Araucaria Project, viz., the irregular galaxies in the Local Group and a number of spiral galaxies in the nearby Sculptor Group (we are currently expanding our work to several of the more massive spiral galaxies in both hemispheres, including M83, M31, and M81). Since Cepheid variables can be most easily discovered in optical photometric bands, where their light curves display the typical sawtooth shapes and the amplitudes of the light variations are large, we have performed extensive optical (VI) wide-field imaging surveys for Cepheid variables in all our target galaxies. These surveys have discovered the first-ever reported Cepheids in the Sculptor galaxies NGC 55 (Pietrzynski et al. 2006b), NGC 247, and NGC 7793 (Pietrzynski et al. 2007, in preparation), and have greatly enhanced the number of known Cepheids with excellent light curves in the optical V and I bands in the Local Group (NGC 6822, Pietrzynski et al. 2004; NGC 3109, Pietrzynski et al. 2006c) and in the Sculptor Group spiral galaxy NGC 300 (Gieren et al. 2004).

The last of the irregular galaxies of the Local Group for which our project has not yet provided a modern new survey for Cepheids is the WLM (Wolf-Lundmark-Melotte) galaxy. In this paper we report on the results of such an extensive survey that has detected a large number of new Cepheid variables in WLM, greatly expanding the list of 15 Cepheid variables that had been previously discovered by Sandage & Carlson (1985, hereafter SC85) from blue and yellow photographic plates taken with the Palomar Hale 5 m and the Las Campanas 2.5 m du Pont reflectors between 1952 and 1983. All of the SC85 Cepheids in WLM have periods less than 10 days, and therefore, their usefulness for distance determination had been somewhat restricted. Our new Cepheid catalog given in § 3 of this paper contains 60 Cepheid variables in WLM with periods down to 1.6 days, increasing the known Cepheid population in WLM by a factor of 4. Most importantly, we can also show from our data that there is one truly long-period Cepheid (54 days) in WLM; the absence of such objects had been a major puzzle, which was suspected to be a consequence of the low metallicity of the young stellar population in WLM (SC85). For distance determination, the discovery of such a long-period Cepheid variable is clearly relevant and we exploit it in § 4 of this paper.

Our paper is organized as follows. In § 2 we describe our observations, reductions, and calibrations. In § 3 we present the catalog of Cepheid variables discovered from our wide-field images, including their periods and mean magnitudes. In § 4 we present the period-luminosity (PL) relations resulting from our new data and use these relations to determine the distance to WLM. In § 5 we discuss our results, and in § 6 we summarize the main conclusions of this paper.

2. OBSERVATIONS, REDUCTIONS, AND CALIBRATIONS

All the data presented in this paper were collected with the Warsaw 1.3 m telescope at Las Campanas Observatory. The telescope was equipped with a mosaic 8K $\times$ 8K detector, with a field of view of about $35' \times 35'$ and a scale of about $0.25''$ pixel^{-1}. For more instrumental details on this camera, the reader is referred to the OGLE Web site.[2] The V images of WLM were secured on 101 different nights between 2001 December and 2003 December. In addition, 24 I-band images were collected in 2003. The exposure time was set to 900 s in both filters.

Preliminary reductions (i.e., debiasing and flat-fielding) were done with the IRAF[3] package. Then, point-spread function photometry was obtained for all stars in the same manner as described in Pietrzyński et al. (2002). Independently, the data were reduced with the OGLE-III pipeline based on the image subtraction technique (Udalski 2003; Woźniak 2000).

In order to accurately calibrate our photometry onto the standard system our target was monitored during three photometric nights in 2000–2006, each time together with a large number of photometric standard stars. On 2000 September 9, WLM was observed with the OGLE-II instrumental system (e.g., a one-chip 2048 $\times$ 2048 pixel CCD camera) together with some 20 standards from the Landolt fields spanning a wide range of colors ($-0.14 < V - I < 1.54$) and observed at very different air masses. The transformation from the OGLE-II system onto the Landolt system was extremely well established from extensive observations of a large number of standard stars over several observing seasons in the course of the OGLE-II project (e.g., Udalski et al. 1998; Udalski 2000). Therefore, we adopted the following transformations:

$$
\begin{aligned}
V - I &= 0.969(v - i) + \mathrm{const}_{V-I}, \\
V &= v - 0.002(V - I) + \mathrm{const}_{V}, \\
I &= i + 0.029(V - I) + \mathrm{const}_{I},
\end{aligned}
\tag{1}
$$

where the lowercase letters v and i denote the aperture instrumental magnitudes normalized to 1 s exposure time, and the color coefficients are those derived by the OGLE team. The extinction coefficients and zero points were derived from our data. The residuals did not exceed 0.04 mag (see Fig. 1) and did not show any significant dependence on color or magnitude. The accuracy of the zero points is estimated to be better than 0.02 mag in both filters.

In order to check the color coefficients provided by the OGLE team we also derived a full set of transformation coefficients. Then, the instrumental magnitudes were transformed using our coefficients and the OGLE ones, and the results were compared. The resulting differences in magnitude were smaller than 0.007 mag in each band.

We also observed WLM together with a large set of Landolt standards covering a large range of colors ($-0.14 < V - I < 1.95$) and at widely different air masses with the OGLE-III mosaic camera on the same 1.3 m Warsaw telescope on two different photometric nights. WLM was located on two of the eight chips of the camera (chip 2 and chip 3). Since in principle the transformation equations for each chip may have different color coefficients and zero points, the selected sample of standard stars was observed on each of the individual chips, and transformation coefficients were derived independently for each chip, on each night. The following transformations were obtained for chips 2 and 3:

$$
\begin{aligned}
V - I &= 0.939(v - i) + \mathrm{const}_{V-I}, \\
V &= v - 0.032(V - I) + \mathrm{const}_{V}, \\
I &= i + 0.031(V - I) + \mathrm{const}_{I} \quad (\text{chip } 2),
\end{aligned}
\tag{2}
$$

[2] Available at http://ogle.astrouw.edu.pl/~ogle/index.html.

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

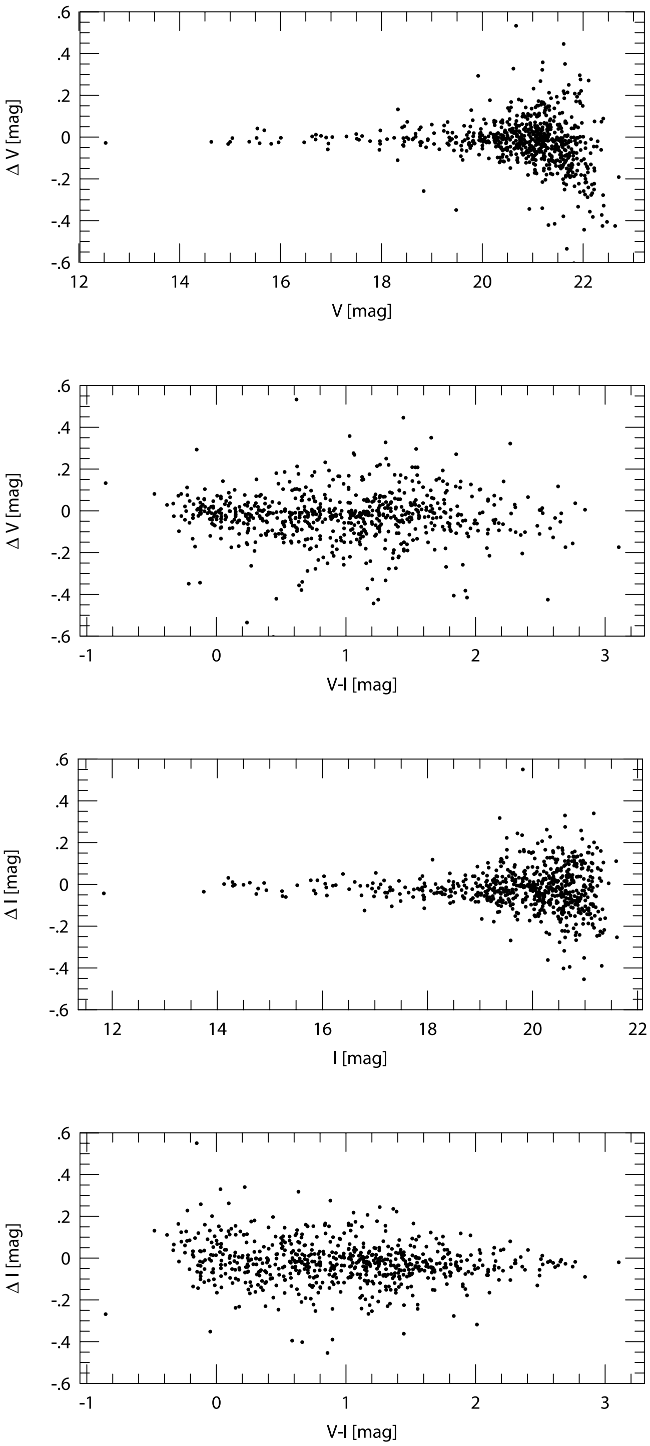

FIG. 1.—Comparison of the photometric zero points in our V- and I-band photometry of WLM obtained from the OGLE-II single chip and the OGLE-III mosaic camera. The independent zero-point determinations are consistent to better than 0.02 mag, and there are no significant trends with color or magnitude in the data.

$$V - I = 0.936(v - i) + \mathrm{const}_{V-I},$$

$$V = v - 0.030(V - I) + \mathrm{const}_V,$$

$$I = i + 0.037(V - I) + \mathrm{const}_I \quad (\text{chip } 3). \tag{3}$$

The resulting color coefficients are consistent with those derived to calibrate our mosaic data from the same telescope and camera for NGC 6822, NGC 3109, and NGC 55, other galaxies studied in the Araucaria Project (see Lee et al. 1993a; SC85). It is worth noting that the color coefficients in equations (1), (2), and (3) are very small, showing that both instrumental systems adjust very closely to the standard Cousins system.

To correct the possible small variation of the photometric zero points in V and I over the mosaic, the "correction maps" established by Pietrzynski et al. (2004) were used. These maps were already applied to correct our photometry obtained in the field of NGC 6822 (Pietrzynski et al. 2004) and NGC 3109 (Pietrzynski et al. 2006c). Comparison with other studies given in these papers revealed that these maps allow us to correct the zero-point variations down to a level of better than 0.03 mag.

The differences between the mosaic camera zero points obtained on the two independent photometric nights were found to be smaller than 0.03 mag in each filter and for both chips. In addition, the comparison of the photometry obtained with the OGLE-II and OGLE-III instrumental systems revealed that the differences in the zero points in both V and I bands are smaller than 0.02 mag and do not correlate in any significant way with magnitude or color (see Fig. 1). As a result of all this comparative work, we are sure that the V and I magnitudes from the two cameras used in this study are consistent at the 1%–2% level. This can also be seen in the quality of the Cepheid light curves, particularly for the brightest variable, presented in Figure 2.

In order to perform an external check of our photometry we compared it to the recent results obtained by McConnachie et al. (2005), who kindly provided us with their data. While the zero-point difference in the V band is reassuringly small (about 0.02 mag, within the errors), the mean difference in I amounts to 0.22 mag, in the sense that our I magnitudes are fainter than the corresponding McConnachie et al. magnitudes for WLM stars by this amount. Also, there is a clear color trend in the sense that for blue stars, our and McConnachie et al.'s I-band magnitudes agree very well, but for redder stars there is an increasing discrepancy, with McConnachie et al.'s magnitudes becoming increasingly brighter than ours. Since all the external checks on our I-band magnitudes obtained with the same telescope and cameras in our previously studied Araucaria target galaxies always yielded good agreement with the photometry of other authors, and since our mosaic camera I-band photometry agrees extremely well with the OGLE-II single-chip photometry, which is calibrated to better than 1%, we conclude that there must be a problem with the I-band data of McConnachie et al., the origin of which remains unknown to us, but which could be related to the use of a nonstandard I filter in their work. Unfortunately, we are not aware of any other source of I-band photometry for WLM with which we could directly compare our data. Therefore, we constructed the I-band luminosity function for RGB stars in WLM using our new photometry and measured the tip of the red giant branch (TRGB) magnitude to be 20.91 ± 0.08 mag. This result is in good agreement with the I-band TRGB magnitude determinations obtained for this galaxy by Lee et al. (1993b; 20.85 ± 0.05 mag) and by Minniti & Zijlstra (1997; 20.80 ± 0.05 mag), indicating that our present I-band photometric zero point has been correctly determined, within the stated small uncertainties. From the internal and external checks we have made, any systematic zero-point error in our present I-band magnitudes is limited to less than 2%.

3. CEPHEID CATALOG

All stars identified in our photometry of WLM were searched for photometric variations with periods between 0.2 and 100 days, using the analysis-of-variance algorithm (Schwarzenberg-Czerny 1989). In order to distinguish the Cepheids from other types of

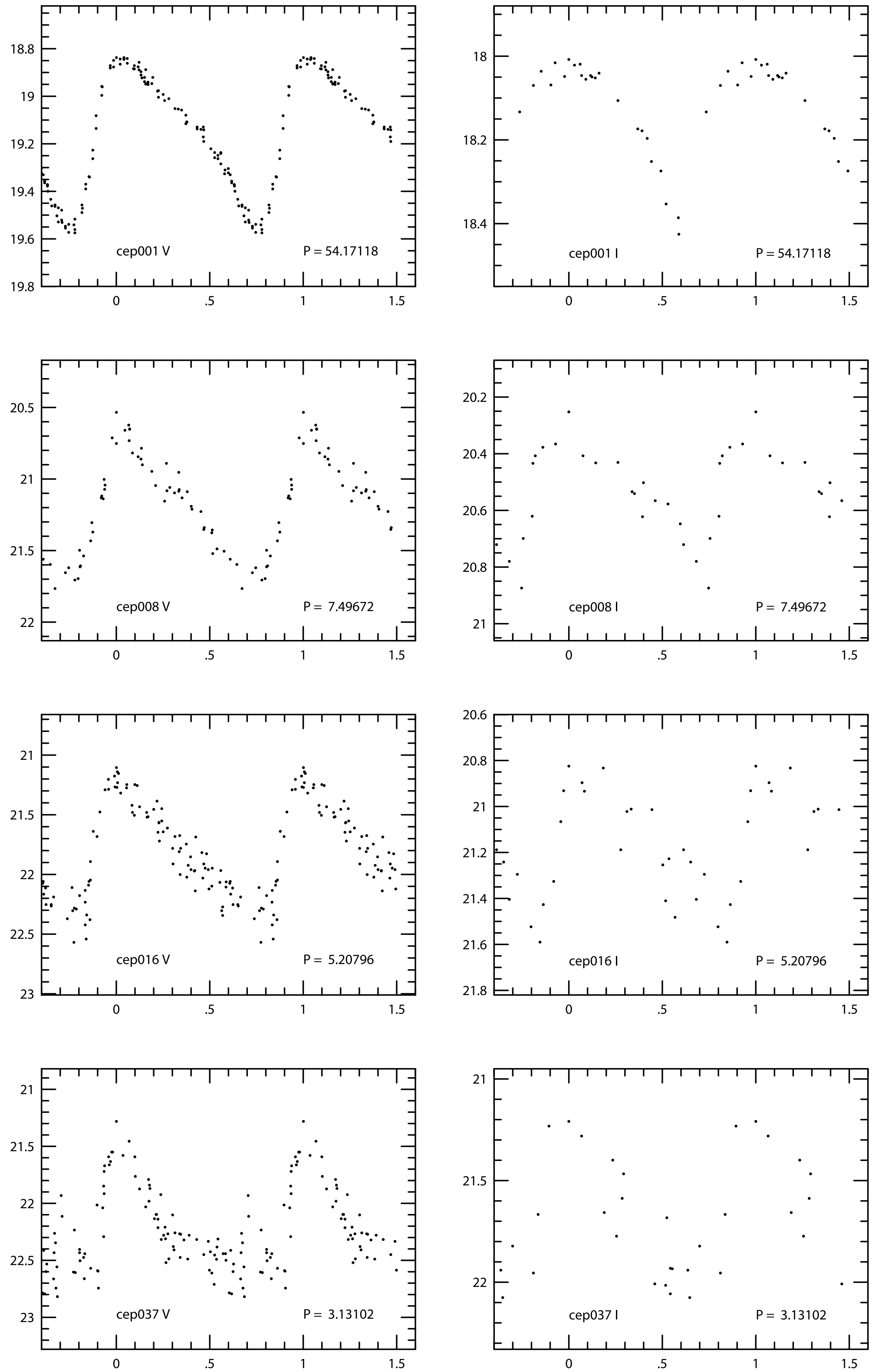

Fig. 2.—Phased *V*- and *I*-band light curves for some Cepheids of different periods in our WLM catalog. These light curves are representative for the light curves of other Cepheid variables of similar periods.

variable stars we applied the criteria defined by Pietrzyński et al. (2002b). The light curves of all the variables identified as Cepheid candidates were fit by Fourier series of order 2. We then rejected those objects with *V* amplitudes smaller than 0.4 mag, in agreement with the procedure that we applied in the previous studies in this series. In principle, one might expect a few very low amplitude Cepheids close to the center of the Hertzsprung progression (in the period range 10–13 days, depending on the metallicity) or located close to the red edge of the Cepheid instability strip. These latter Cepheids have decreased amplitudes due to the increased efficiency in the convective energy transport (Bono et al. 2000) but seem to be normal with respect to their

TABLE 1
CEPHEIDS IN WLM

ID	R.A. (J2000.0)	Decl. (J2000.0)	P (days)	T_0	$\langle V \rangle$ (mag)	$\langle I \rangle$ (mag)	$\langle W_I \rangle$ (mag)	Remarks
cep001	00 01 57.48	−15 24 50.9	54.17118	2,452,200.59519	19.124	18.145	16.628	V12
cep002	00 01 54.33	−15 30 00.1	10.34249	2,452,201.65246	21.110	20.352	19.177	
cep003	00 01 54.03	−15 27 05.2	10.33645	2,452,202.34982	20.975	20.247	19.119	
cep004	00 02 03.30	−15 26 23.4	10.32152	2,452,200.25769	21.270	20.416	19.092	
cep005	00 01 54.68	−15 29 55.0	8.63110	2,452,194.74995	21.182	20.471	19.369	V21
cep006	00 01 57.08	−15 30 56.6	8.12579	2,452,195.29021	21.350	20.600	19.438	V24
cep007	00 02 00.19	−15 24 11.4	8.12051	2,452,200.62453	21.319	20.629	19.559	
cep008	00 01 56.56	−15 27 15.6	7.49672	2,452,202.09693	21.170	20.511	19.490	V7
cep009	00 01 57.07	−15 27 25.7	7.34322	2,452,199.48513	21.297	20.573	19.451	V48
cep010	00 01 56.40	−15 24 33.0	7.32485	2,452,198.47873	21.314	20.661	19.649	V11
cep011	00 01 57.04	−15 29 36.9	6.64055	2,452,201.99522	21.258	20.640	19.682	V8
cep012	00 02 00.51	−15 25 23.2	6.15754	2,452,201.17636	21.423	20.736	19.671	
cep013	00 01 53.27	−15 29 40.5	6.05309	2,452,197.85970	21.775	21.086	20.018	V37
cep014	00 02 10.26	−15 33 31.9	5.56746	2,452,197.36270	21.557	20.973	20.068	
cep015	00 01 59.91	−15 24 49.4	5.43153	2,452,200.95046	21.544	21.043	20.266	V50
cep016	00 01 55.20	−15 24 26.8	5.20796	2,452,201.89881	21.760	21.090	20.052	
cep017	00 01 57.32	−15 29 03.9	5.12851	2,452,201.58810	21.963	21.281	20.224	
cep018	00 01 56.16	−15 25 44.8	5.02134	2,452,197.96031	21.964	21.211	20.044	
cep019	00 02 00.12	−15 25 15.1	4.92341	2,452,199.88515	21.507	21.009	20.237	
cep020	00 01 59.50	−15 25 57.4	4.91559	2,452,201.10843	21.708	21.002	19.908	V29
cep021	00 02 01.47	−15 23 20.1	4.86831	2,452,199.59021	21.993	21.356	20.369	
cep022	00 02 00.20	−15 25 17.2	4.71140	2,452,198.82984	22.012	21.278	20.140	
cep023	00 02 00.85	−15 25 04.9	4.61967	2,452,197.94467	22.181	21.371	20.116	
cep024	00 01 52.13	−15 27 05.8	4.36958	2,452,198.61530	21.904	21.318	20.410	V66
cep025	00 02 02.37	−15 23 36.9	4.05416	2,452,199.04623	22.231	21.597	20.614	
cep026	00 02 02.23	−15 26 45.1	3.97606	2,452,199.52316	22.375	21.490	20.118	
cep027	00 01 55.96	−15 26 22.1	3.86503	2,452,199.27326	22.262	21.546	20.436	
cep028	00 01 55.92	−15 29 02.9	3.83017	2,452,201.20424	21.528	20.990	20.156	
cep029	00 02 01.15	−15 32 09.2	3.82512	2,452,198.77320	22.076	21.478	20.551	V38
cep030	00 01 51.94	−15 27 11.1	3.74707	2,452,198.98222	22.129	21.479	20.472	
cep031	00 01 54.57	−15 25 18.1	3.65377	2,452,200.36249	21.606	21.044	20.173	
cep032	00 02 00.60	−15 26 21.8	3.47735	2,452,201.41880	22.033	21.248	20.031	
cep033	00 01 58.99	−15 24 37.3	3.30475	2,452,199.14958	22.193	21.655	20.821	
cep034	00 02 00.46	−15 26 44.2	3.24559	2,452,199.75819	22.107	21.536	20.651	
cep035	00 01 58.10	−15 28 57.9	3.20292	2,452,199.69890	22.106	21.620	20.867	
cep036	00 01 59.18	−15 24 18.1	3.13908	2,452,200.37271	22.075	21.700	21.119	V1
cep037	00 02 00.13	−15 24 20.8	3.13102	2,452,199.64936	22.200	21.582	20.624	
cep038	00 02 01.47	−15 25 08.9	3.03891	2,452,199.44801	22.301	21.544	20.371	
cep039	00 01 58.00	−15 23 39.5	3.02576	2,452,201.61526	22.413	21.669	20.516	
cep040	00 02 04.72	−15 25 11.0	2.96301	2,452,199.33434	21.907	21.272	20.288	
cep041	00 01 50.67	−15 28 55.4	2.92899	2,452,202.05423	22.550	21.888	20.862	
cep042	00 02 01.68	−15 32 13.8	2.92454	2,452,202.46634	22.289	21.804	21.052	
cep043	00 01 58.03	−15 30 38.6	2.88896	2,452,201.16317	22.002	21.462	20.625	
cep044	00 01 57.18	−15 31 30.1	2.83459	2,452,199.52500	22.028	21.468	20.600	
cep045	00 01 54.73	−15 22 29.8	2.80077	2,452,201.45090	21.926	21.397	20.577	
cep046	00 01 57.84	−15 22 09.3	2.74179	2,452,200.78817	22.976	22.500	21.762	
cep047	00 02 01.59	−15 19 50.0	2.64641	2,452,200.62767	22.971	22.208	21.025	
cep048	00 02 09.54	−15 22 53.6	2.52010	2,452,201.90797	22.474	...	...	
cep049	00 01 59.67	−15 25 16.3	2.51004	2,452,200.24177	22.055	21.729	21.224	
cep050	00 02 00.74	−15 28 58.4	2.48031	2,452,201.87459	21.575	20.958	20.002	
cep051	00 01 58.61	−15 26 11.6	2.38903	2,452,199.88267	21.533	20.631	19.233	
cep052	00 02 03.77	−15 28 49.7	2.38701	2,452,200.11112	22.001	21.567	20.894	
cep053	00 02 03.63	−15 32 42.7	2.35613	2,452,201.71542	22.916	22.540	21.957	
cep054	00 02 03.22	−15 24 55.6	2.34579	2,452,200.82716	22.761	22.053	20.956	
cep055	00 02 00.77	−15 26 25.5	2.33770	2,452,200.24656	21.459	21.118	20.589	
cep056	00 02 09.55	−15 31 35.0	2.29048	2,452,200.50653	22.908	22.298	21.352	
cep057	00 01 59.85	−15 28 59.8	2.16776	2,452,201.55259	22.877	22.046	20.758	
cep058	00 01 54.61	−15 28 37.0	2.12863	2,452,201.26721	22.358	21.748	20.802	
cep059	00 02 00.00	−15 25 59.8	1.64746	2,452,201.88190	22.395	21.315	19.641	Blend
cep060	00 01 53.57	−15 29 57.0	1.62627	2,452,201.78043	22.640	22.234	21.605	

NOTES.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Table 1 is also available in machine-readable form in the electronic edition of the *Astronomical Journal*.

luminosities, and are therefore in principle useful for distance determinations via PL relations. In our database for WLM we found only two such objects, but we decided to omit them for the distance analysis because of the poor quality of their light curves and also to be consistent with our earlier studies. In any case, including these objects would not change any of the results and conclusions reached in this paper.

For the 60 stars passing our selection criteria, mean *V* and *I* magnitudes were derived by integrating their light curves, which had been previously converted onto an intensity scale, and converting the results back onto the magnitude scale. The periods of the 60 Cepheids in our catalog range between 1.6 and 54.2 days. The accuracy of the period values is about $10^{-4}P$ days. There is only one truly long-period Cepheid in WLM, variable cep001 in our catalog, which is given in Table 1. The variable with the next-longest period, cep002, has a period of 10.3 days. Since our images cover the spatial content of WLM to almost 100%, it seems that there are definitively no other Cepheids with periods longer than 10.3 days in WLM except cep001. This bright variable had already been discovered and classified as a Cepheid by SC85 (their variable V12; entries in the "Remarks" column in Table 1 give the Cepheid identifications of SC85), but due to their limited set of photographic data they determined a wrong period for this Cepheid (7.9 days). For all the other variables classified as Cepheids by SC85 their Cepheid nature is confirmed in our study, although for most variables the new periods differ quite significantly from the values given in SC85, which is not a surprise given the quality and quantity of our new data, compared to the data SC85 had at their disposal for their very important and pioneering study of the stellar content of WLM. We remark that of the 15 Cepheids discovered by SC85 two objects are not in our catalog, V40 and V67. The variable V67 of SC85 falls between the chips of the mosaic camera we used to image the WLM galaxy, and therefore, we have no data for this object. Variable V40 shows a Cepheid-like light curve from our data with a period close to the one found by SC85, but its amplitude is below our threshold value, which explains why it has not entered our catalog. The low amplitude of this variable is also evident in its *B* light curve shown in SC85.

A comparison of the light curves of the 14 Cepheids in WLM common with SC85 shows a dramatic increase in quality and, therefore, in the accuracy of the periods and mean intensity magnitudes we were able to derive from our new data. In Figure 2, we show the *V* and *I* light curves for several of the Cepheids in our database whose quality is representative for other Cepheids of similar periods. One can see that down to a period of 3 days, corresponding to a mean *V* magnitude of about 22.2, the light curves are still very well defined and allow the determination of the mean *V* magnitude with a precision of about 0.05 mag. The mean *I* magnitudes of the Cepheids are somewhat less precise due to the smaller number of data points.

In Figure 3, we show the locations of the WLM Cepheids in the V, $V-I$ color-magnitude diagram (CMD), where they delineate the expected Cepheid instability strip (Chiosi et al. 1992; Simon & Young 1997). The locations of the 60 variables in our catalog in the CMD lends further support to their correct identifications as classical Cepheids. Again, it is remarkable to see the only long-period variable in this diagram, at a V magnitude almost 2 mag brighter than all the other shorter period, lower mass Cepheids we see in WLM. It still seems a challenging problem for stellar evolution theory to explain the existence of just one high-mass star in the Cepheid instability strip, given the rather abundant population of young, massive stars in this galaxy, as evidenced by its blue supergiant population (Bresolin et al. 2006).

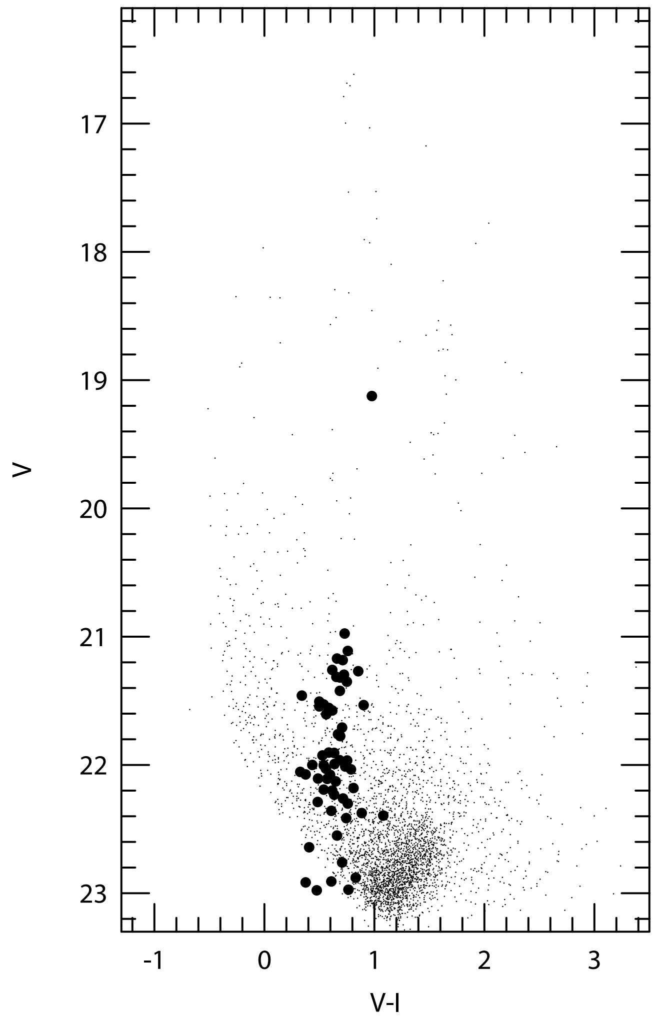

Fig. 3.—The V, $V-I$ magnitude-color diagram for WLM. The Cepheids discovered in our survey are marked with circles. They fill the expected region of the Cepheid instability strip for fundamental mode pulsators in this diagram, yielding supporting evidence that the classification of the variables as classical fundamental-mode Cepheids is correct.

In Table 2, we report the individual *V* and *I* observations of the Cepheids in Table 1. The full Table 2 is available in the electronic edition of the *Astronomical Journal*.

4. PL RELATIONS AND DISTANCE DETERMINATION

In Figure 4, we show the *V*-band PL relation resulting from the data in Table 1 for the Cepheids in our sample with $\log P(\text{days}) > 0.5$. The corresponding *I*-band PL relation defined by these stars is shown in Figure 5. These (35) objects represent the subsample, which should in principle be free of the Malmquist bias that is introduced by retaining Cepheid variables close to the faint magnitude cutoff of the photometry. This bias, if not accounted for, would tend to systematically decrease the derived distance to the galaxy. A sample of Cepheids with $\log P(\text{days}) > 0.5$ should also be reasonably free of first overtone pulsators, whose existence at very short pulsation periods was impressively shown in the LMC work of the OGLE-II project (Udalski et al. 1999). Keeping only Cepheid variables above this period cutoff also assures us, in the case of the present photometry, that only Cepheid light curves of high quality are used for the distance analysis.

A closer inspection of the sample of Cepheids in Figures 4 and 5 reveals three objects that are clearly too bright for their

TABLE 2
Individual V and I Observations

Object	Filter	HJD−2,450,000	Magnitude	σ_{mag}
cep001	V	2859.767260	18.992	0.011
cep001	V	2870.773910	19.139	0.010
cep001	V	2877.719380	19.311	0.011
cep001	V	2884.726910	19.531	0.011
cep001	V	2902.671760	18.838	0.007
cep001	V	2906.700510	18.876	0.008
cep001	V	2910.673090	18.946	0.010
cep001	V	2915.629040	19.010	0.012
cep001	V	2930.643450	19.237	0.011
cep001	V	2934.624860	19.378	0.011
cep001	V	2942.576190	19.560	0.014
cep001	V	2950.543020	18.961	0.019
cep001	V	2954.584470	18.837	0.014
cep001	V	2959.548090	18.884	0.007
cep001	V	2963.554610	18.947	0.010
cep001	V	2966.523340	18.979	0.010
cep001	V	2968.541650	19.018	0.011
cep001	V	2971.552980	19.051	0.010
cep001	V	2972.535090	19.053	0.011
cep001	V	2973.555780	19.058	0.012

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

respective periods. These objects are cep028 and cep031, which stand out in both PL planes, and the star cep032, which seems too bright for its period in the I-band PL plane. These stars are likely to be strongly blended by nearby companion stars that are not resolved in our photometry, but they could also be overtone pulsators, which at these periods near 4 days are still occurring, albeit in small numbers. In view of this we decided to choose the cutoff period, in the case of WLM, at $\log P(\text{days}) = 0.7$ (5.0 days). This choice yields the best compromise between retaining a statistically significant sample of stars for the determination of the PL relations (19 Cepheids) and avoiding a possibly significant contamination of the sample by overtone Cepheids and/or heavily blended objects. As we show below, the distance determination to WLM is, however, not significantly affected by the choice of the cutoff period: both samples, using $\log P = 0.5$ or 0.7 as the cutoff period, yield distance moduli to WLM that differ by only 0.05 mag, which is within the uncertainty of the present distance determination of WLM from our Cepheid photometry.

From an inspection of Figures 4 and 5, it is obvious that the slopes of the PL relations in V and I adopted from the LMC Cepheids as given by the OGLE-II project provide excellent fits to the present data for the WLM Cepheids. Indeed, fits to a straight line to our data yield the following slopes for the PL relations: -2.57 ± 0.16, -2.93 ± 0.12, and -3.15 ± 0.16 in V, I, and W_I, the reddening-free Wesenheit band (see Fig. 6), respectively. These values are consistent with the corresponding OGLE slopes of the LMC Cepheid PL relation of −2.775, −2.977, and −3.300 (Udalski 2000) at the level of 1 σ. In the case of WLM, the low number of long-period Cepheids and the large gap in period between 10 and 54 days make an accurate determination of the slope of the PL relations impossible, but the data are clearly very well fit by the slopes adopted from the LMC Cepheids, supporting the conclusion that any systematic change of the PL relation slope

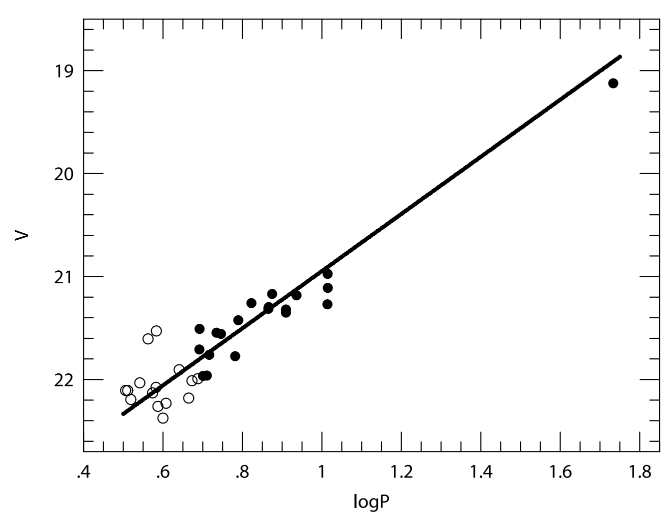

Fig. 4.—PL relation from the 35 Cepheid variables in WLM with $\log P$ (days) > 0.5. Filled circles show those Cepheids with $\log P > 0.7$. This sample of 19 stars is unaffected by Malmquist bias and contamination with possible overtone pulsators, and the mean magnitudes of the variables are determined to better than 1% (random uncertainty). The slope of the fitting line is taken from the LMC Cepheid PL relation of the OGLE-II project and provides an excellent fit to the data.

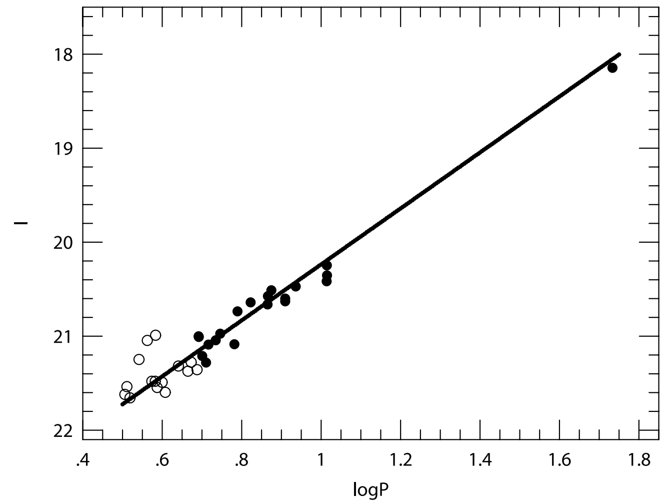

Fig. 5.—Same as Fig. 4, but for the I band.

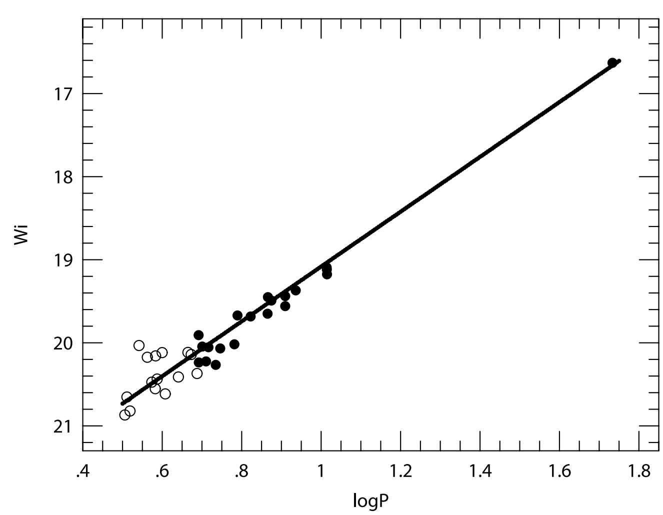

Fig. 6.—Same as Fig. 4, but for the reddening-independent $(V - I)$ Wesenheit magnitudes. The very small scatter in this diagram for the Cepheids, denoted by the filled circles, indicates that this sample is free of significantly blended stars that would tend to decrease the distance of WLM derived from these data.

going from the LMC Cepheids to the more metal-poor WLM Cepheids must be very small. Our present data are certainly fully consistent with the assumption of identical slopes of the Cepheid PL relations in V, I, and W_I for WLM and the LMC.

In view of this finding, we are justified in adopting the extremely well determined OGLE slopes to derive the distance to WLM, as we have already done in the previous papers of this series. This leads to the following equation: [log P(days) > 0.7; 19 Cepheids]:

$$V = -2.775 \log P + (23.772 \pm 0.037),$$

$$I = -2.977 \log P + (23.275 \pm 0.028),$$

$$W_I = -3.300 \log P + (22.418 \pm 0.045).$$

Using the 35 Cepheids with log P(days) > 0.5, we obtain the following results:

$$V = -2.775 \log P + (23.722 \pm 0.037),$$

$$I = -2.977 \log P + (23.214 \pm 0.030),$$

$$W_I = -3.300 \log P + (22.382 \pm 0.036).$$

Adopting, as in our previous papers, a value of 18.50 mag for the true distance modulus to the LMC, a value of $E(B-V) = 0.02$ mag for the foreground reddening toward WLM (Schlegel et al. 1998), and the reddening law of Schlegel et al. (1998) [$A_V = 3.24E(B-V), A_I = 1.96E(B-V)$] we obtain the following reddening-corrected distance moduli for WLM in the three different bands:

1. [19 Cepheids with log P(days) > 0.7]:

$$(m-M)_0(W_I) = 25.144 \text{ mag},$$

$$(m-M)_0(I) = 25.142 \text{ mag},$$

$$(m-M)_0(V) = 25.050 \text{ mag}.$$

2. [35 Cepheids with log P(days) > 0.5]:

$$(m-M)_0(W_I) = 25.093 \text{ mag},$$

$$(m-M)_0(I) = 25.082 \text{ mag},$$

$$(m-M)_0(V) = 25.014 \text{ mag}.$$

As we already mentioned above, the difference in the true distance moduli in the respective bands for the two samples is on the order of the uncertainty on the zero points of the respective PL relation, demonstrating that the choice of the period cutoff for the WLM Cepheid sample used for the distance determination is not a source of significant systematic error on the WLM distance. We adopt 25.144 ± 0.040 (random error) mag as our best determination of the true distance modulus of WLM from the reddening-independent $V-I$ Wesenheit magnitudes of its Cepheids. We discuss this result and estimate its total uncertainty in § 5.

5. DISCUSSION

The current distance result for the WLM dwarf irregular galaxy is based on a sizeable sample of Cepheid variables with excellent light curves that mostly have been discovered in our present wide-field imaging survey. Very importantly, we have discovered one long-period variable that allows a check on the slope of the Cepheid PL relation in WLM and partly resolves the mystery of the absence of such stars in WLM previously discussed by SC85. Our data in the period–mean magnitude planes in V, I, and W_I are very well fit with the PL relation slopes obtained for the LMC Cepheids by the OGLE-II project, further supporting the evidence that the slope of the Cepheid PL relation is independent of metallicity down to very low values of [Fe/H] or [O/H]. For WLM, the mean oxygen abundance of three blue supergiant stars was recently measured to be about −0.6 dex (Bresolin et al. 2006), suggesting that its older population of Cepheid variables is likely to have a mean metallicity close to −1.0 dex, which is indeed considerably more metal-poor than the mean [Fe/H] of −0.34 dex derived for a sample of LMC Cepheids by Luck et al. (1998). This is in agreement with the result of Udalski et al. (2001) for the Cepheid PL relation in another metal-poor Local Group dwarf irregular galaxy, IC 1613, which also does not show any sign for a change of the slope of the PL relation at very low metallicities. The recent results of Gieren et al. (2005b) from a comparison of the Cepheid PL relations in the LMC and Milky Way, and those of Macri et al. (2006) from a comparison of the Cepheid PL relations for two fields of very different mean metal abundance in the maser galaxy NGC 4258 observed with *HST* ACS, also support the constancy of the slope of the Cepheid PL relation in optical bands up to solar metallicity. Very importantly, a completely independent confirmation of this has very recently come from the *HST* parallaxes of a number of nearby Milky Way Cepheids derived by Benedict et al. (2006), which also suggest that there is no difference between the slope of the PL relation in the Milky Way galaxy and the LMC.

The current distance determination to WLM is subject to the several well-known sources of systematic uncertainty in such studies. We have made a great effort to calibrate our data as accurately as possible, and our discussion in § 2 in this paper shows that we can confidently assume that our photometric zero points in V and I are accurate to better than ±0.03 mag. The sample of Cepheid variables in our study is large enough to ensure that our distance result is not severely affected by the problem of a possible incomplete filling of the instability strip. We do, however, note that the range of periods for which a complete filling of the instability strip can be assumed is rather limited (5–11 days). We recall that we are not attempting to use our data to fit slopes to the PL diagrams in Figures 4–6, whose values would sensitively depend on the exact position of the one long-period Cepheid with respect to the ridge line in the instability strip, but rather adopt the slopes from the LMC PL relations. It is reassuring to see that the long-period Cepheid in our sample falls very close to the fitting lines in all filters, suggesting that this star is located close to the center of the Cepheid instability strip. This conclusion is also clearly supported by the position of object cep001 in the CMD in Figure 3. All the physical information on this star available to us (shape of the light curve, amplitude, mean magnitude, color, and period) supports the idea that this object is a normal classical Cepheid. Although it may appear surprising, our database clearly indicates that there are no other Cepheids in the large period gap between the objects cep001 and cep002 in WLM.

Our discussion in § 4 has also shown that our adopted choice of the cutoff period, necessary to exclude overtone pulsators from the sample and to address the problem of Malmquist bias, is not affecting our distance result by more than ±0.05 mag. The small dispersion of the data points in Figure 6 around the mean PL relation suggests that the process of eliminating the influence of reddening (both foreground and a possible additional variable reddening produced inside WLM itself) by the construction of the reddening-free Wesenheit magnitudes of the Cepheids has worked very well. This is likely due to the fact that our Cepheid photometry is affected very little by blending with unresolved, relatively bright nearby companion stars, which is a more serious problem in the spiral galaxies of higher stellar density in our program. Yet, even in the case of NGC 300, at about twice the distance of WLM (Gieren et al. 2005a), Bresolin et al. (2005) were able to show from a comparison of ground-based data to *HST* ACS data that the effect of blending on the distance modulus is less than 0.04 mag. We therefore believe that the distance modulus of WLM from the Wesenheit PL relation eliminates reddening as a significant source of systematic error in our study. Also, the fact that the distance result from the *I* band is practically identical to the one from the Wesenheit band seems to indicate that the total reddening affecting the WLM Cepheids in our database is very small, which in turn means that in addition to the very small 0.02 mag foreground reddening there is very little additional dust absorption *intrinsic* to WLM. A follow-up study of the WLM Cepheids in the near-IR *J* and *K* bands will shed more light on this and allow an accurate determination of any residual dust absorption inside WLM, as we have done in our previous studies in several of the target galaxies of our project. Unfortunately, so far we have not been able to collect such near-IR images of WLM under photometric conditions but hope to do so in the near future.

As a conclusion, our present distance modulus determination of WLM from the Wesenheit magnitudes of its long(er) period Cepheid population has a total estimated systematic uncertainty of ± 0.07 mag, when the different contributions discussed about are added in quadrature. Therefore, we obtain as our best result from the current study a true distance modulus of the WLM galaxy of 25.144 ± 0.03 (random) ± 0.07 (systematic) mag, equivalent to a total uncertainty of $\pm 4\%$. This estimation of the total uncertainty does *not* include, however, the uncertainty on our adopted value of 18.50 mag for the distance of the LMC. A thorough discussion of this value will be provided in a forthcoming paper once the Cepheid distances to all Araucaria Project target galaxies have been measured. At this point, we just mention that the recent absolute calibration of the Cepheid PL relation of Macri et al. (2006) in NGC 4258, which is tied to the geometric maser distance to this galaxy, implies a LMC distance modulus of 18.41, but the uncertainty on this value estimated by the authors of that paper makes it clearly compatible with our adopted LMC distance of 18.50. It seems clear that the adopted distance to the LMC continues to be the largest individual source of systematic error on modern Cepheid-based distance determinations to nearby galaxies like the present one, which have succeeded in beating down other systematics to the level of a few percent. Work to improve this situation will be extremely important over the next years. As a positive note, evidence is now clearly mounting that the *slope* of the PL relation is independent of metallicity over the broad range from solar down to about -1.0 dex allowing us to use the slope values determined in the LMC by the microlensing projects with confidence for Cepheid-based distance determinations to other galaxies, including those showing pronounced radial metal abundance variations in their disks.

Finally, we note that our improved Cepheid distance determination to WLM puts the galaxy some 0.2–0.3 mag further away than the value derived from the TRGB *I*-band magnitude (Lee et al. 1993b, -24.87 ± 0.08; Minniti & Zijlstra 1997, -24.75 ± 0.1; this paper, -24.91 ± 0.08). A possible interpretation for this discrepancy is that the metal-poor WLM Cepheids are, at a given period, intrinsically fainter in *V* and *I* than their more metal-rich counterparts in the LMC. Indeed, the sign and size of the discrepancy between the present distance to WLM from its Cepheids and the one derived from the TRGB magnitude is consistent with the metallicity dependence of the zero point of the Cepheid PL relation of 0.2–0.3 mag dex^{-1} found by Sakai et al. (2004, their Fig. 15). On the other hand, our current work on the distances of nearby galaxies from the blue supergiant flux-weighted gravity-luminosity relation (Kudritzki et al. 2003) supports the 25.14 mag true distance modulus derived in this paper from the WLM Cepheids (R. P. Kudritzki et al. 2007, in preparation), so the interpretation that the Cepheid distance to WLM is longer than the TRGB distance because of a metallicity effect on the PL relation zero point may be premature at this time. A full discussion of the effect of metallicity on the zero point of the Cepheid PL relation in different bands will be presented in a later stage of our project when distances from a variety of methods to all target galaxies of the project will have been determined; hopefully, this will lead to a very accurate calibration of the metallicity dependence of the PL relation in various photometric bands.

6. CONCLUSIONS

The main conclusions of this paper can be summarized as follows:

1. We have conducted an extensive wide-field imaging survey for Cepheids in the Local Group dwarf irregular galaxy WLM. From *V*-band images obtained on 101 different nights, we have found 60 Cepheids with periods down to 1.6 days. Our Cepheid survey in WLM should be essentially complete down to a period of about 3 days. We have determined accurate periods and mean magnitudes for all variables in the *V*, *I*, and Wesenheit bands.

2. We have discovered the first (and only) long-period Cepheid variable in WLM, cep001 in our catalog, with a period of 54.2 days. This variable had already been discovered before by SC85, but their low-quality data had led them to derive a wrong period for this Cepheid.

3. From the data in our catalog we have constructed PL relations in the *V*, *I*, and reddening-independent Wesenheit band. We find that our data are very well fit by the slopes of the corresponding PL relations determined in the LMC by the OGLE-II project, supporting the conclusion that the slope of the PL relation defined by the more metal-poor Cepheids in WLM is identical to the one in the LMC.

4. We have derived absorption-corrected distance moduli to WLM from the data in *V*, *I*, and *W*. Our adopted best value for the WLM distance modulus from the reddening-independent Wesenheit magnitudes of the Cepheids is 25.144 ± 0.03 (random) ± 0.07 (systematic) mag. The excellent agreement between the *W*-band and *I*-band distance modulus values hints at very little dust absorption intrinsic to WLM.

5. The total uncertainty of our present distance determination of $\sim\pm 4\%$ does not include the contribution from the uncertainty on the adopted LMC distance of 18.50 to which our present distance determination to WLM is tied, as in the previous papers of the Araucaria Project. As in our previous Cepheid studies of NGC 6822 (Gieren et al. 2006), IC 1613 (Pietrzynski et al. 2006a), NGC 3109 (Pietrzynski et al. 2006c; Soszynski et al. 2006), NGC 300 (Gieren et al. 2004, 2005a), and NGC 55 (Pietrzynski et al. 2006b), the total error on our Cepheid distance to WLM due to the variety of factors discussed in § 5 is clearly smaller than the contribution coming from the adopted LMC distance, implying that the main obstacle to significant progress in the measurement of the *absolute* distances to nearby galaxies is

our continuing difficulty to obtain a truly high-quality measurement of the distance to the LMC.

6. With WLM, there is now another galaxy in our project whose Cepheid distance can be compared to the distances we will measure for our target galaxies from a variety of other methods, like the flux-weighted gravity-luminosity relationship of Kudritzki et al. (2003) for blue supergiant stars. It is another step toward the main goal of the Araucaria Project, viz., an accurate determination of the environmental dependences of different stellar distance indicators, with the corresponding reduction on the systematic error on the Hubble constant determined from secondary distance indicators that will be recalibrated from the standard candles we are investigating once their environmental dependences are well established.

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