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DIRECT DISTANCES TO CEPHEIDS IN THE LARGE MAGELLANIC CLOUD: EVIDENCE FOR A UNIVERSAL SLOPE OF THE PERIOD-LUMINOSITY RELATION UP TO SOLAR ABUNDANCE

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ABSTRACT

We have applied the infrared surface brightness (ISB) technique to derive distances to 13 Cepheid variables in the LMC that span a period range from 3 to 42 days. From the absolute magnitudes of the variables calculated from these distances, we find that the LMC Cepheids define tight period-luminosity (PL) relations in the *V*, *I*, *W*, *J*, and *K* bands that agree exceedingly well with the corresponding Galactic PL relations derived from the same technique and are significantly steeper than the LMC PL relations in these bands observed by the OGLE-II Project in *V*, *I*, and *W* and by Persson and coworkers in *J* and *K*. We find that the LMC Cepheid distance moduli we derive, after correcting them for the tilt of the LMC bar, depend significantly on the period of the stars, in the sense that the shortest period Cepheids have distance moduli near 18.3, whereas the longest period Cepheids are found to lie near 18.6. Since such a period dependence of the tilt-corrected LMC distance moduli should not exist, there must be a systematic, period-dependent error in the ISB technique not discovered in previous work. We identify as the most likely culprit the *p*-factor, which is used to convert the observed Cepheid radial velocities into their pulsational velocities. By demanding (1) a zero slope on the distance modulus versus period diagram and (2) a zero mean difference between the ISB and ZAMS fitting distance moduli of a sample of well-established Galactic cluster Cepheids, we find that $p = 1.58(\pm 0.02) - 0.15(\pm 0.05)\log P$, with the *p*-factor depending more strongly on Cepheid period (and thus luminosity) than indicated by past theoretical calculations. When we recalculate the distances of the LMC Cepheids with the revised *p*-factor law suggested by our data, we not only obtain consistent distance moduli for all stars but also decrease the slopes in the various LMC PL relations (and particularly in the reddening-independent *K* and *W* bands) to values that are consistent with the values observed by OGLE-II and Persson and coworkers. From our 13 Cepheids, we determine the LMC distance modulus to be 18.56 ± 0.04 mag, with an additional estimated systematic uncertainty of $\sim$0.1 mag. Using the same corrected *p*-factor law to redetermine the distances of the Galactic Cepheids, the new Galactic PL relations are also found consistent with the observed optical and near-infrared PL relations in the LMC. Our main conclusion from the ISB analysis of the LMC Cepheid sample is that, within current uncertainties, there seems to be no significant difference between the slopes of the PL relations in the Milky Way and LMC. With literature data on more metal-poor systems, it seems now possible to conclude that the *slope* of the Cepheid PL relation is independent of metallicity in the broad range in [Fe/H] from -1.0 dex to solar abundance, within a small uncertainty. The new evidence from the first ISB analysis of a sizable sample of LMC Cepheids suggests that the previous, steeper Galactic PL relations obtained from this technique were caused by an underestimation of the period dependence in the model-based *p*-factor law used in the previous work. We emphasize, however, that our current results must be substantiated by new theoretical models capable of explaining the steeper period dependence of the *p*-factor law, and we will also need data on more LMC field Cepheids to rule out remaining concerns about the validity of our current interpretation.

Subject headings: Cepheids — distance scale — galaxies: distances and redshifts — Magellanic Clouds — stars: oscillations

1. INTRODUCTION

Since the discovery of the Cepheid period-luminosity (PL) relation almost 100 years ago by Miss H. Leavitt, Cepheid variables have played a key role in the establishment of the extragalactic distance scale. With modern telescopes and detectors, light curves of individual Cepheid variables can be measured with good accuracy out to distances of about 20 Mpc, as demonstrated in the *Hubble Space Telescope* (*HST*) Key Project on the Extragalactic Distance Scale (Freedman et al. 2001). Fitting the observed PL relation in a galaxy to a fiducial relation calibrated in our own Milky Way, or in the LMC, a robust distance estimate of the program galaxy can be obtained. The *HST* Key Project used such Cepheid-based distances to some 30 nearby galaxies to calibrate far reaching secondary methods of distance determination in these galaxies that were then used to provide distance estimates to more remote galaxies, distant enough for a determination of the Hubble constant being free of biases due to galaxy peculiar velocities. An accurate determination of the present-day expansion rate of the universe is necessary, in turn, to constrain other cosmological parameters with ever increasing accuracy. More stringent constraints on H_0 from improved optical/near-IR work on Cepheids and secondary distance indicators will be an important complement to constraints coming from *WMAP* and the Cosmic Background Imager in the radio part of the electromagnetic spectrum.

The fiducial PL relation used in the Cepheid process of distance determination is obviously of key importance for the final distance results for the program galaxies. Unfortunately, it has been notoriously difficult to calibrate the Cepheid PL relation in the Milky Way. Even using state-of-the-art present-day telescopes and instrumentation, Cepheid variables in the Milky Way, with the exception of the very nearest ones (e.g., Benedict et al. 2002), are too distant for accurate determinations of their distances with direct geometrical methods; therefore, one has to resort to more indirect techniques. Over the past four decades, the two most important methods to calibrate the PL relation have been the use of zero-age main-sequence (ZAMS) fitting distances to Cepheids in open clusters and associations and the use of Baade-Wesselink–type techniques, which take advantage of the observed variations of a Cepheid in magnitude, color, and radial velocity to derive its distance and mean radius. While the cluster method has suffered some degree of complication after *Hipparcos* studies revealed that stellar evolution effects on the location of the ZAMS in the Hertzsprung-Russell diagram of open clusters are stronger than anticipated (van Leeuwen 1999), Baade-Wesselink–type techniques have greatly improved in accuracy through the move from the optical to the near-infrared domain and are now arguably the most accurate tool to measure the distances to individual Cepheids. In particular, the infrared surface brightness (ISB) technique, as calibrated by Fouqué & Gieren (1997, hereafter FG97), has allowed the derivation of distances to individual Galactic Cepheids with an accuracy of an estimated 5% (Gieren et al. 1997), and the Galactic Cepheid PL relation has been calibrated from this technique in optical and near-infrared bands in Gieren et al. (1998), Fouqué et al. (2003), and most recently Storm et al. (2004). In this work, it was found that the slope of the Galactic PL relation appears to be significantly *steeper*, in all photometric bands, than the slope of the corresponding PL relation in the Magellanic Clouds as established by the different microlensing surveys and in particular by the OGLE-II survey (Udalski et al. 1999; Udalski 2000). The question is then, is this finding real, reflecting perhaps an effect of metallicity on the slope of the PL relation, or is there some hitherto unknown systematic error in the ISB distance results for the Galactic Cepheids that causes the PL slope as determined from the ISB distances to be steeper than the one observed in the Magellanic Clouds, which is extremely well established from many hundreds of Cepheids in both the LMC and SMC? The investigation of this question is of the utmost importance for the use of Cepheids as distance indicators, given that many nearby spiral galaxies, including a subsample of the galaxy sample used by the *HST* Key Project team, are of near-solar or even supersolar metallicity. Using for these galaxies the LMC OGLE-II PL relation as the fiducial in the distance determination would lead to systematic errors in the distance moduli of these metal-rich galaxies by several tenths of a magnitude, depending on the period ranges spanned by the extragalactic Cepheid samples, if the steeper Galactic slope of the PL relation were indeed true.

One straightforward way to check on the validity of our Galactic ISB Cepheid distance results is to apply the technique directly on a number of Cepheids in the LMC and to construct from these data a PL relation in the LMC, which can be compared to the Galactic relation. Such a comparison should shed some light on the question of the universality of the PL relation and is the purpose of this study. Some time ago, we set out to obtain the necessary high-quality data for the application of the ISB technique on a number of Cepheid variables in the LMC. Optical photometry of a sample of long-period field Cepheids was obtained by Moffett et al. (1998). We also obtained complete data sets of optical and near-IR (*JK*) photometry, as well as radial velocity curves, for a sample of short-period LMC Cepheids in the rich cluster NGC 1866 (Storm et al. 2005). A preliminary distance determination for the Cepheid HV 12198 in NGC 1866 was already published by Gieren et al. (2000). For the longer period Cepheids studied by Moffett et al. (1998), there are excellent radial velocity curves in the literature that have been measured with the CORAVEL instrument at La Silla (Imbert 1987). Very recently, near-infrared light curves for these stars of excellent quality have been published by Persson et al. (2004), completing the data sets necessary to determine ISB distances to these objects. There are now 13 Cepheids in the LMC with periods from 3 to 42 days with excellent data for the ISB analysis. We derive a direct distance value for each of these Cepheids in this paper, and we demonstrate that the PL relation in the LMC obtained from these data is *identical*, within small uncertainties, to the Galactic PL relation obtained from exactly the same technique and precepts. Since we know the *true* LMC Cepheid PL relation from the work of the OGLE group on more than 600 stars and from the recent extensive work of Persson et al. (2004) in near-infrared bands, we investigate the reason(s) for the discrepancy between the OGLE-II/Persson and ISB results and identify the *p*-factor used to convert the observed radial velocities of Cepheids into their pulsational velocities as the most likely culprit for a period-dependent systematic error in the ISB distance results. Recalibrating the period dependence of the *p*-factor with our LMC Cepheid distance data, we show that this leads to a corrected slope of the Galactic Cepheid PL relation that is in excellent agreement with the observed OGLE-II PL relation in the LMC and SMC, suggesting (with data on other galaxies) that in the metallicity range from -1.0 dex to solar there is no significant variation in the slope of the Cepheid PL relation in either of the optical or near-infrared bands. We point out a number of caveats and future work that has to be done to put this conclusion on a firmer basis.

2. THE INFRARED SURFACE BRIGHTNESS TECHNIQUE

The central idea behind the surface brightness technique is to calibrate the relation between the stellar surface brightness and an appropriate color index. Once such a calibration is at hand, photometry yields the stellar angular diameter and, in the case of a Cepheid variable, the variation of its angular diameter through its pulsation cycle. The angular diameter curve of a Cepheid measured this way can then be combined with its linear displacement curve, which is obtained from an integration of the observed radial velocity curve of the variable star. A linear regression analysis of pairs of angular diameters and linear displacements of the stellar surface observed at the same phases yields both the distance of the star and its mean radius.

The surface brightness technique was originally introduced by Barnes & Evans (1976). FG97 provided a recalibration of the technique providing two major improvements: first, they used accurate interferometrically determined angular diameters of giants and supergiants bracketing the Cepheid color range that had become available at the time, to improve the calibration of the surface brightness–color relation; and second, in addition to the visual $(V - R)$ color index used in previous work, they extended the calibration to the near-infrared $(V - K)$ and $(J - K)$ colors. That such an extension of the technique to the near-infrared would significantly reduce the random errors in the technique was already suggested by the previous work of Welch (1994). It was borne out by the results for the distances and radii of a large sample of Galactic Cepheid variables measured with the V, $V - K$ version of the ISB technique by Gieren et al. (1997, 1998) and more recently by Fouqué et al. (2003) and Storm et al. (2004). In these papers, it was demonstrated that the ISB technique seems able to produce distances and radii of Cepheid variables accurate to 5% if the data sets used in the analyses are of very high quality. In particular, it was already shown by Barnes et al. (1977) that the method is very insensitive to errors in the assumed *reddenings* of the Cepheids. This is true for both the $V - R$ and the near-infrared $V - K$ and $J - K$ versions of the technique. In addition, in their recent paper Storm et al. (2004) were able to demonstrate that at the present level of accuracy, the technique is also insensitive to both metallicity and gravity variations in the Cepheids.

One of the principal potential systematic uncertainties of the ISB technique refers to the assumption that the pulsating Cepheid variables follow the same surface brightness–color relation as stable, nonpulsating giants and supergiants. The interferometric work on Cepheid variables that has been conducted in recent years by different groups (e.g., Nordgren et al. 2002; Kervella et al. 2004a) has impressively shown that this is indeed the case, to a high degree of accuracy. Nordgren et al. (2002) recalibrated the $V - K$ surface brightness–color relation from the interferometrically measured mean angular diameters of a number of nearby Cepheids and found agreement with the FG97 calibration at the 4% level. With improved data on nine Cepheids and a total of 145 individual interferometric measurements for them, the visual surface brightness versus $(V - K)$ relation from direct interferometric observations of Cepheids is even closer to the FG97 relation, showing agreement at the 2% level (Kervella et al. 2004b). Very recently, the pulsations of the nearby Cepheid l Car, which due to its proximity and large linear diameter has the largest angular diameter (3 mas) of all Galactic Cepheids, were resolved by the ESO VLTI with very high accuracy, and it was demonstrated in that paper that for l Car the angular diameters measured by interferometry agree at the 1% level with those coming from the FG97 calibration of the ISB technique (Kervella et al. 2004c). As a result of all these recent investigations, it seems now clear that Cepheid angular diameters, as well as their variations over the pulsation cycles, can be very accurately predicted by the surface brightness–color calibration of FG97.

The other possibly serious source of systematic uncertainty in the ISB technique (and in fact in any Baade-Wesselink–type technique) refers to the projection or p-factor, which is used to convert the radial velocities into pulsational velocities of the stellar surface. Since the p-factor scales the radius variations, it enters directly into the derived distance of a Cepheid: if p is, say, overestimated by 5%, the resulting distance is 5% too large as well. An accurate determination of the p-factor, as well as its dependence on Cepheid luminosity and hence period, is therefore crucial for the method.

The p-factor not only is a geometrical projection factor but also depends on the structure of the atmosphere and even on the way radial velocities are measured. First computations of the p-factor based on line profiles derived from model Cepheid atmospheres were performed by Parsons (1972). Depending on the spectral resolution, he found values ranging between 1.30 and 1.34 as appropriate. Hindsley & Bell (1986) investigated from a new set of models the value of the p-factor appropriate if the radial velocities were measured with a Griffin-type photoelectric radial velocity spectrometer like the CORAVEL instrument (Baranne et al. 1979). From their results, they argued for a slightly higher value, 1.36, for p than Parsons. Gieren et al. (1993) noted that the models of Hindsley & Bell (1986) actually predicted a mild dependence of the p-factor on pulsation period and determined

$$p = 1.39 - 0.03 \log P$$

as a reasonable approximation to the results from these models. In all subsequent work of our group, particularly in the work of Gieren et al. (1998) and Storm et al. (2004), this slightly period-dependent p-factor was used in the ISB analyses of Cepheid variables.

In the most recent and probably so far most sophisticated approach to the problem, Sabbey et al. (1995) found that the p-factor may even be variable over the pulsation cycle for one given Cepheid. This conclusion was derived from non-LTE models, whereas LTE models gave a constant p-factor for a given Cepheid, which seems in better agreement with the fact that for the best-observed Cepheids, the angular diameter and linear displacement curves agree exceedingly well (e.g., Fig. 2 in Storm et al. 2004), which should not be the case if the p-factor was indeed significantly phase dependent. We also believe that this excellent match between the shapes of angular diameter and linear displacement curves for the best-observed Cepheids is a strong indication that the ISB technique is not significantly affected by problems with a changing distance between the atmospheric layers in which the spectral lines and the continuum are produced. We have, however, found that for a sizable subsample of the Cepheids we have analyzed with the ISB technique there is a discrepancy between the shapes of the angular diameter and linear displacement curves in the phase range *near minimum radius*, which could be caused by a significant variation of the p-factor in this phase range. As discussed in Storm et al. (2004), our standard procedure to cope with this fact is to exclude points near minimum radius (in the phase range 0.8–1.0) in the ISB solutions. The work of Sabbey et al. (1995) also suggested that the way the radial velocity is determined, and therefore the instrument and reduction procedure employed for the radial velocity determination, can have an effect on the final result for the p-factor appropriate for the analysis of a particular set of radial velocity observations. Storm et al. (2004) were able to perform a high-precision test on this possibility by comparing very high quality data sets for the Cepheids U Sgr and X Cyg obtained with

TABLE 1
ISB Distance and Radius Solutions for LMC Cepheids

Cepheid	log P (days)	$(m - M)_0$ (mag)	$\sigma_{(m-M)}$ (mag)	Δm (mag)	$(m - M)_{0,\mathrm{LMC}}$ (mag)	R ($R_\odot$)	σ_R ($R_\odot$)	Δ_ϕ
HV 12199	0.421469	18.336	0.094	−0.058	18.394	25.0	1.1	0.025
HV 12203	0.470427	18.481	0.092	−0.059	18.540	28.3	1.2	0.050
HV 12202	0.491519	18.289	0.072	−0.059	18.348	28.5	1.0	0.025
HV 12197	0.497456	18.165	0.058	−0.058	18.223	25.9	0.7	−0.020
HV 12204	0.536402	18.202	0.044	−0.059	18.261	28.3	0.6	0.010
HV 12198	0.546887	18.314	0.028	−0.059	18.373	29.8	0.4	0.015
HV 12816	0.959466	18.328	0.087	−0.076	18.404	54.1	2.2	0.035
HV 12815	1.416910	18.296	0.028	−0.075	18.371	126.3	1.6	−0.025
HV 899	1.492040	18.769	0.013	0.017	18.752	160.2	0.9	0.030
HV 879	1.566170	18.532	0.040	0.044	18.488	163.3	3.0	0.025
HV 909	1.574990	18.397	0.029	0.048	18.349	155.1	2.1	−0.055
HV 2257	1.595150	18.788	0.028	0.054	18.734	197.7	2.6	0.010
HV 2338	1.625350	18.663	0.023	0.070	18.593	199.4	2.2	−0.005

TABLE 2
Individual Radial Velocity Observations of HV 12816

HJD 2,400,000	Vr	σ_{Vr}
51,163.699	270.88	0.30
51,164.672	271.81	0.30
51,165.711	276.32	0.30
51,167.719	279.12	0.30
51,168.699	286.94	0.30
51,169.566	293.09	0.30
51,170.586	294.08	0.30
51,171.590	282.75	0.30
51,172.703	270.87	0.30
51,174.598	275.52	0.30
51,175.844	275.69	0.30
51,176.582	278.32	0.30
51,178.836	293.81	0.30
51,179.832	294.01	0.30
51,181.633	271.19	0.30
51,182.555	271.41	0.30
51,193.762	275.97	0.30
51,545.797	271.72	0.27
51,546.785	271.47	0.13
51,547.746	273.84	0.09
51,548.773	277.06	0.17
51,548.781	276.33	0.14
51,549.770	276.36	0.07
51,550.703	282.53	0.08
51,551.770	290.72	0.08
51,552.754	294.74	0.17
51,564.738	270.77	0.14
51,565.602	272.42	0.10
51,566.703	276.93	0.09
51,567.672	275.20	0.08
51,568.594	280.05	0.08
51,569.641	287.95	0.08
51,570.707	294.64	0.14
51,571.664	293.19	0.21
51,854.660	284.18	0.38
51,909.762	276.43	0.41
52,264.832	279.61	0.27
52,270.746	286.08	0.24
52,595.801	276.83	0.12
52,601.699	282.88	0.34
52,601.758	281.23	0.30
52,603.758	271.32	0.22

the CORAVEL and CfA spectrometers, finding that there is no measurable velocity difference between the two different high-resolution cross-correlation based systems and that at a high level of confidence the *p*-factor to be used for both sets of velocity data should be the same. Therefore, the combination of stars in a sample whose radial velocity curves have all been measured by cross-correlation with a high-resolution spectrometer, as is the case for the LMC Cepheids studied in this paper, should not introduce any significant additional systematic uncertainty in the ISB distance solutions. However, the preceding discussion clearly shows that there is still some significant uncertainty as to the correct value of the *p*-factor to be used in Baade-Wesselink–type analyses of Cepheids, including its correct dependence on the stellar luminosity and thus period. We come back to this problem in § 4 in the light of our distance results for the LMC Cepheids analyzed in this paper.

3. NEW DISTANCE SOLUTIONS FOR LMC CEPHEIDS

In our ISB solutions for long-period LMC Cepheids reported in this section, we have used exactly the same code and precepts as employed by Storm et al. (2004) in their analysis of a sample of 34 Galactic Cepheids and five SMC Cepheids and in their recent work on Cepheid variables in the rich LMC cluster NGC 1866 (Storm et al. 2005). In particular, we have allowed for small

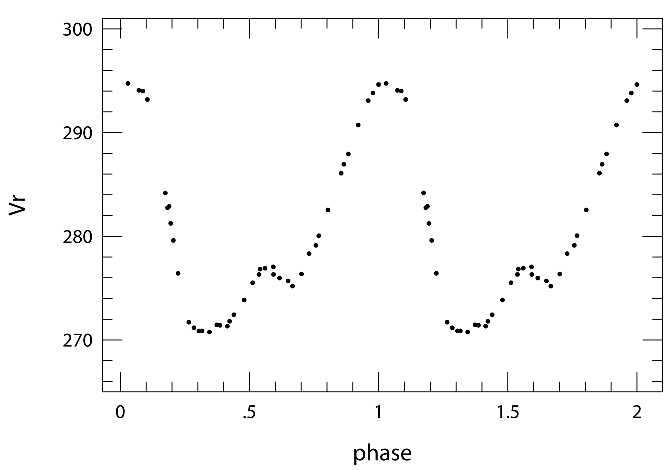

Fig. 1.—Radial velocity curve for the LMC Cepheid HV 12816 from our new measurements in Table 2.

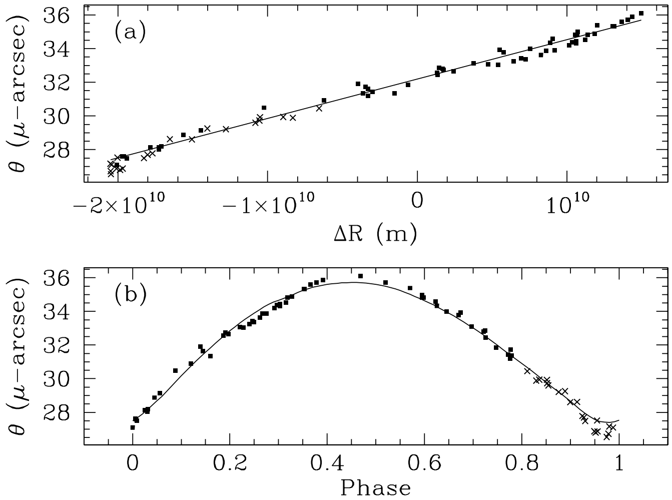

FIG. 2.—Infrared surface brightness distance solution for the LMC Cepheid HV 2257. The symbols represent the photometrically determined angular diameters, and the line in (*a*) shows the bisector fit to the filled symbols. The line in (*b*) delineates the angular diameter curve obtained from integrating the radial velocity curve of the star at the derived distance. Crosses in the 0.8–1.0 phase interval were eliminated from the fit.

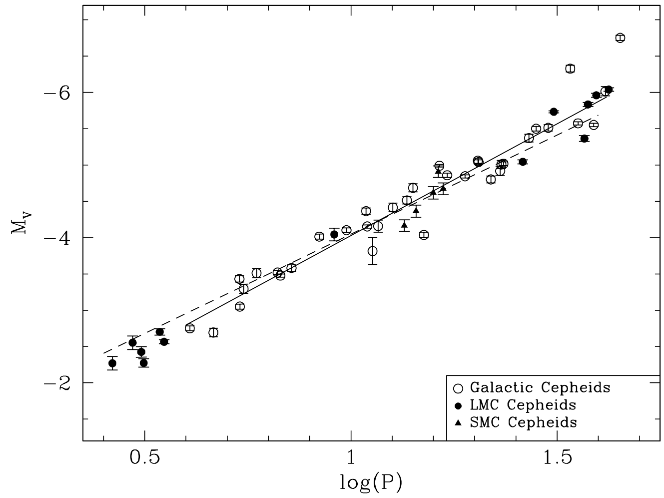

FIG. 3.—Absolute *V*-band magnitudes derived from the ISB distances of 38 Milky Way, 13 LMC, and 5 SMC Cepheids. The canonical *p*-factor relation was used for the calculation of the ISB distances of all stars. The solid line is the best fit to the Galactic data. The dashed line is the *V*-band PL relation in the LMC from the OGLE-II project, for an assumed LMC distance modulus of 18.50. The ISB-based PL relation defined by the LMC Cepheids agrees exceedingly well with the Milky Way ISB-based relation; both are significantly steeper than the observed OGLE-II relation.

phase shifts to optimize the agreement between the observed angular diameter and linear displacement curves of the Cepheids. In all of our solutions, and in a consistent way with the Galactic Cepheid analyses, we have only used data in the 0.0–0.8 phase ranges, omitting the data near minimum radius for which there is evidence that they could be affected by systematic problems that are not present in the 0.0–0.8 phase interval. We also remark here that a recent determination of the distances to the 34 Galactic Cepheids analyzed by Storm et al. (2004) with the Bayesian statistical analysis code of Barnes et al. (2003) (as opposed to the maximum likelihood technique used in our analysis) has provided agreement of the two sets of distances to better than 1% (Barnes et al. 2005), which is a strong confirmation of the statistical validity of our code used for the surface brightness distance and radius determinations.

Table 1 lists the 13 LMC Cepheids for which data sets exist to carry out an ISB solution on them. The six short-period stars are members in the rich cluster NGC 1866 and have already been analyzed in Storm et al. (2005). All Cepheids lie in the period range of 3–50 days for which the ISB method has been calibrated in our previous work. Newly determined periods for the stars were derived by minimizing the scatter in their light curves. The reddenings for the long-period stars were adopted from Persson et al. (2004). The optical light-curve data for the long-period variables were taken from Moffett et al. (1998) and supplemented with data from Caldwell & Coulson (1986) for HV 12815, Martin & Warren (1979) for HV 879, and Madore (1975) for HV 2257. Their infrared light curves in *J* and *K* were taken from Persson et al. (2004) and supplemented with data from Laney & Stobie (1986) for HV 879. Radial velocity curves for the long-period Cepheids in our sample have been measured with the CORAVEL instrument by Imbert (1987) for HV 879, HV 899, HV 909, HV 2257, and HV 2338. For HV 12815, we have adopted the radial velocity curve obtained by Caldwell & Coulson (1986). For HV 12816, we present in Table 2 a new and accurate series of radial velocity measurements obtained with the FEROS and CORALIE high-resolution spectrographs at La Silla (F. Kienzle et al. 2005, in preparation). The resulting radial velocity curve of HV 12816 is shown in Figure 1. This 9.1 day Cepheid is important in our current analysis since it fills

TABLE 3
ABSOLUTE MAGNITUDES OF LMC CEPHEIDS

Cepheid	log *P* (days)	$\langle M_V \rangle$ (mag)	$\langle M_I \rangle$ (mag)	$\langle M_J \rangle$ (mag)	$\langle M_K \rangle$ (mag)	$\langle M_W \rangle$ (mag)	$E(B-V)$ (mag)	[Fe/H] (dex)
HV 12199	0.421469	−2.269	−2.870	−3.075	−3.672	−3.777	0.060	−0.50
HV 12203	0.470427	−2.552	−3.153	−3.562	−3.930	−4.060	0.060	−0.50
HV 12202	0.491519	−2.425	−3.050	−3.553	−3.922	−3.992	0.060	−0.50
HV 12197	0.497456	−2.273	−2.918	−3.338	−3.728	−3.891	0.060	−0.50
HV 12204	0.536402	−2.702	−3.239	−3.626	−3.981	−4.050	0.060	−0.50
HV 12198	0.546887	−2.565	−3.202	−3.675	−4.030	−4.165	0.060	−0.50
HV 12816	0.959466	−4.044	−4.630	−5.028	−5.366	−5.514	0.070	. . .
HV 12815	1.416910	−5.044	−5.899	−6.500	−6.988	−7.190	0.070	. . .
HV 899	1.492040	−5.734	−6.543	−7.097	−7.541	−7.763	0.110	. . .
HV 879	1.566170	−5.365	−6.320	−6.989	−7.521	−7.763	0.060	−0.55
HV 909	1.574990	−5.835	−6.597	−7.107	−7.524	−7.747	0.058	−0.27
HV 2257	1.595150	−5.961	−6.860	−7.475	−7.959	−8.216	0.060	−0.36
HV 2338	1.625350	−6.040	−6.922	−7.514	−7.981	−8.254	0.040	−0.37

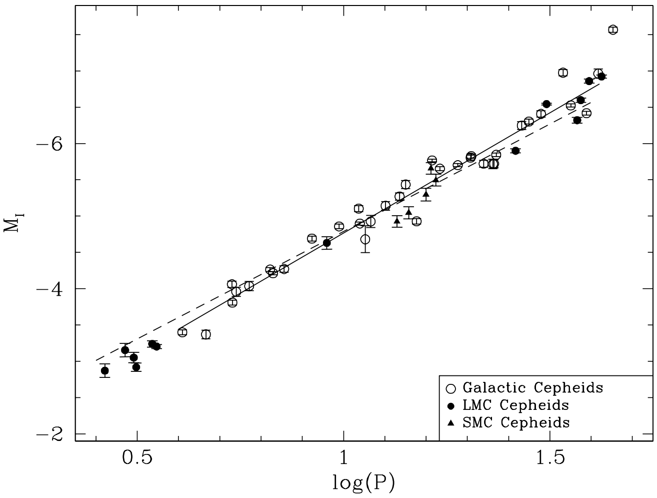

Fig. 4.—Same as Fig. 3, but for the absolute magnitudes in the *I* band.

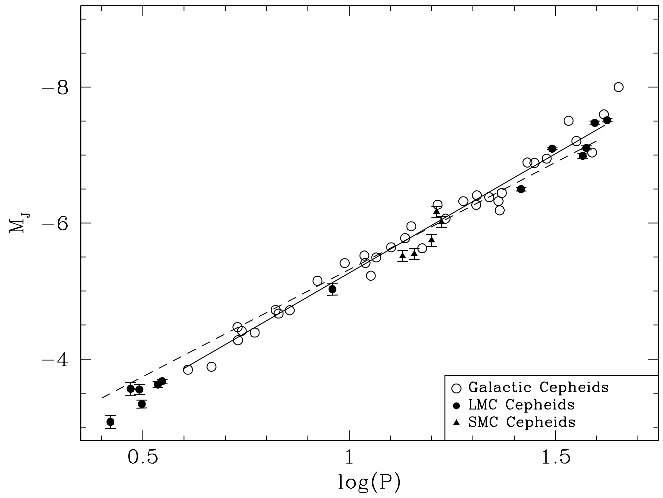

Fig. 6.—Same as Fig. 3, but for the absolute magnitudes in the *J* band. The dashed line is the *J*-band PL relation in the LMC measured by Persson et al. (2004), for an assumed LMC distance modulus of 18.50.

the gap between the short-period NGC 1866 Cepheids, whose periods cluster around 3 days, and the longer period stars of our current LMC Cepheid sample with periods between 26 and 42 days. All photometric data sets available for our LMC Cepheid sample are of excellent quality, comparable to the typical quality of the data sets for the Galactic stars analyzed in Storm et al. (2004). The radial velocity curves are of excellent quality too except the data set for HV 12815, which is somewhat noisier than the data for the other Cepheids.

In Table 1, we present the distance and radius results from our ISB solutions on the 13 LMC Cepheids together with their respective uncertainties. Table 1 also lists the phase shifts between angular diameter and linear displacement curves that were adopted for the various Cepheids (last column). While a part of these observed shifts may be due to intrinsic (unknown) causes, another part is likely due to the fact that the radial velocity and photometric data sets for the Cepheids were not obtained contemporaneously, which can introduce some additional small misalignments between the angular diameter and linear displacement curves due to imperfectly known pulsation periods (Gieren et al. 1997). For all variables, the shifts are satisfactorily small, indicating that the periods are quite well determined in all cases. If we adopted zero phase shifts for all stars, we would slightly increase the random uncertainties on the individual distances and radii, but the conclusions of this paper would not be changed. Our discussion in this paper is concerned with the distance results; the radii of the variables will be discussed in a forthcoming paper.

In Figure 2 we show, as a typical example, the ISB solution on the Cepheid HV 2257 in order to demonstrate that the quality of the LMC Cepheid ISB solutions is as good as the average quality of our Galactic Cepheid distance solutions reported in Storm et al. (2004). In Table 3 we present the absolute magnitudes of the LMC Cepheids in the *VIJK* photometric bands that were calculated from the distances of Table 1 and from the intensity mean apparent magnitudes for the Cepheids in these bands that were determined from the data sets listed above. Table 3 also displays the reddening-free $(V - I)$ absolute Wesenheit magnitudes of the Cepheids [with the Wesenheit magnitudes being defined as $W = V - 2.51(\langle V \rangle - \langle I \rangle)$] and the adopted color excesses from which the absorption corrections were calculated, using the mean ratios of total to selective absorption as given in Fouqué et al. (2003). In the last column, the spectroscopic metallicities of the Cepheids are given as determined in the high-resolution studies of Luck et al. (1998) for the Cepheids HV 879, HV 909, HV 2257, and HV 2338 and by Hill et al. (2000) for

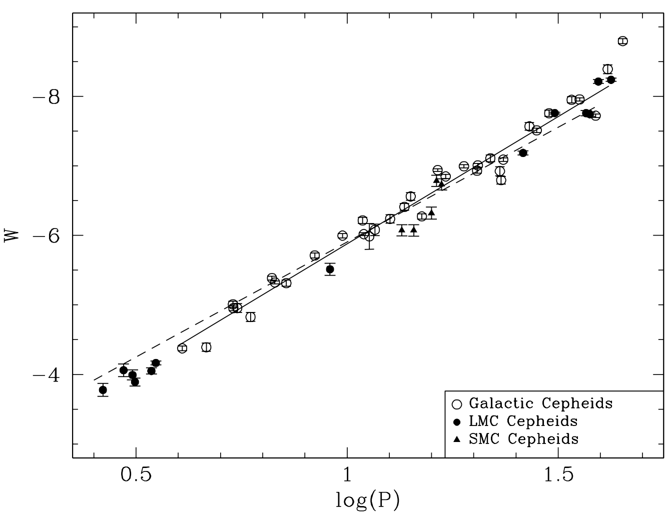

Fig. 5.—Same as Fig. 3, but for the absolute reddening-free *W*-band magnitudes.

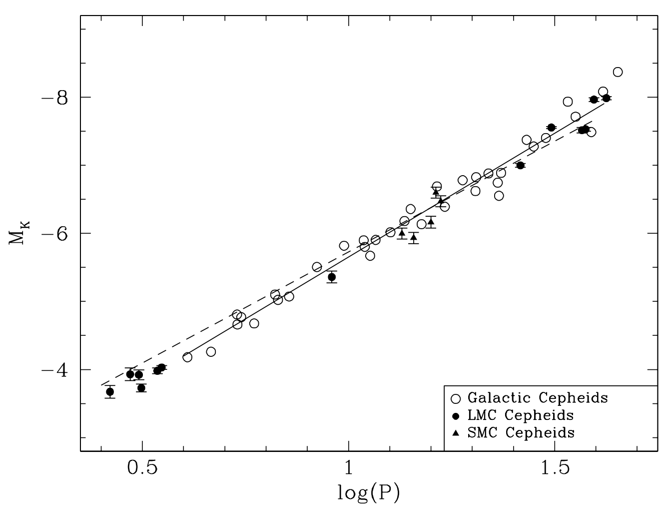

Fig. 7.—Same as Fig. 6, but for the absolute magnitudes in the *K* band.

TABLE 4

SLOPES OF THE PERIOD-LUMINOSITY RELATION FROM THE ISB TECHNIQUE ASSUMING THE CANONICAL *p*-FACTOR LAW

Band	LMC	σ	Milky Way	σ	LMC (OGLE-II/Persson)	σ
V	−3.048	0.093	−3.082	0.133	−2.775	0.031
I	−3.289	0.079	−3.312	0.109	−2.977	0.021
W	−3.650	0.074	−3.660	0.100	−3.300	0.011
J	−3.476	0.078	−3.510	0.095	−3.153	0.051
K	−3.540	0.072	−3.639	0.097	−3.261	0.042

three red giants in NGC 1866 (we assume that the metallicity of the red giants in NGC 1866 is representative for its Cepheids).

4. THE LMC CEPHEID PERIOD-LUMINOSITY RELATION FROM THE ISB TECHNIQUE

In Figures 3–7 we show the LMC Cepheid PL relations in the different photometric bands as defined from our data. Overplotted are the absolute magnitudes of 34 Galactic Cepheids determined from the ISB technique in Storm et al. (2004) and those of an additional two Galactic Cepheids analyzed in this paper. We also show the data for the five SMC Cepheids that were analyzed in Storm et al. (2004) to determine the effect of metallicity on the zero point of the PL relation. Since the five SMC Cepheids span a very narrow range in period, however, they are not useful for constraining the slope of the PL relation in the SMC. Figures 3–7 demonstrate that in *all* bands, the absolute magnitudes of the 13 LMC Cepheids we have studied fit the corresponding Galactic PL relation exceedingly well and are in significant disagreement with the PL relations in the LMC as observed by the OGLE-II project in *VIW* and by Persson et al. (2004) in *JK*. The fits to the Cepheid absolute magnitudes in both the LMC and Milky Way bear this out. The slopes of the corresponding PL relations in the Milky Way and the LMC, as given in Table 4, are nearly identical and agree to a small fraction of their respective uncertainties, whereas the ISB-determined PL slopes in the LMC disagree by 4–5 σ with the slopes observed in *VIWJK* by OGLE-II and Persson et al. (2004), which is clearly significant. It should be stressed that the slopes of the LMC PL relations are rather precisely determined from the ISB distances of the present 13 LMC Cepheids, in spite of the relatively small number of stars available for our analysis, because the period distribution of the stars is favorable for this purpose and the random uncertainties on the absolute magnitudes are small, particularly for the longest period LMC Cepheids.

In Figure 8 we show the *K*-band absolute magnitudes of the Galactic, LMC, and SMC Cepheids together with the absolute magnitudes of seven Galactic Cepheids whose angular diameter curves were measured at the ESO VLTI by Kervella et al. (2004b). Although some of these absolute magnitudes based on interferometry have rather large uncertainties, the data fit very nicely on the Galactic PL relation from the ISB technique and demonstrate the excellent agreement of the interferometrically determined angular diameters with those from our adopted surface brightness–color relation.

The conclusion from the existing data is then that the LMC Cepheid PL relation, as determined from the ISB technique, turns out to be *identical* to the corresponding Galactic relation, within a reasonably small uncertainty, and is significantly at odds with the directly observed and extremely well established PL relations in the LMC from the OGLE-II project in the optical bands and from the work of Persson et al. (2004) in the near-infrared *J* and *K* bands.

A hint to the solution of this problem comes from a comparison of the true distance moduli of the 13 LMC Cepheids in Table 1, which show an unexpected large and systematic deviation in the sense that the long-period Cepheids are found on

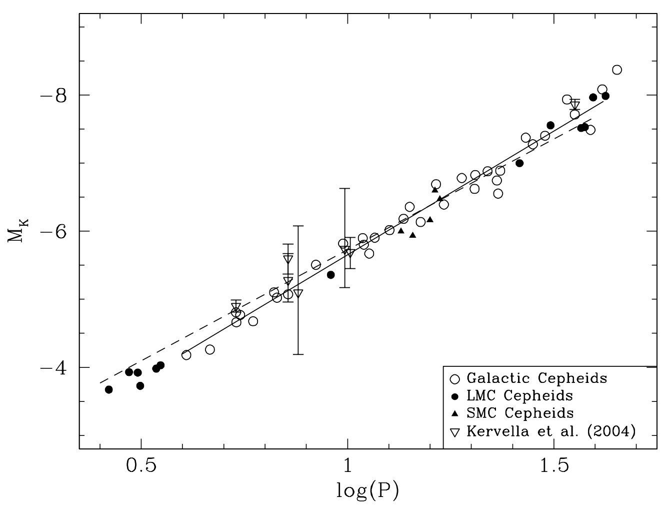

FIG. 8.—Same as Fig. 7. The triangles are the absolute magnitudes of seven Milky Way Cepheids whose angular diameter curves have been measured with the ESO VLTI by Kervella et al. (2004b). Within the error bars, there is very good agreement with the absolute magnitudes of the Milky Way Cepheids whose angular diameters have been determined with our adopted calibration of the surface brightness–color relation.

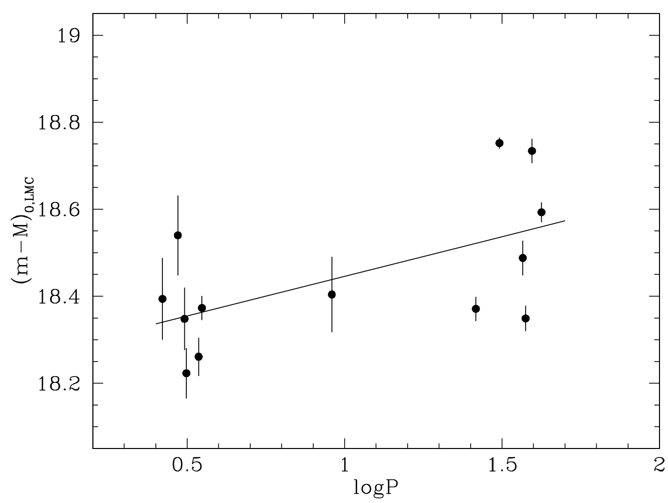

FIG. 9.—ISB-determined true distance moduli for LMC Cepheids, calculated with the canonical *p*-factor law, plotted against their period. The distance moduli have been corrected for the tilt of the LMC plane with respect to the line of sight with the model of van der Marel & Cioni (2001). There is a significant trend of the distance moduli with period.

TABLE 5

Galactic Cluster Cepheid ZAMS Fitting and ISB Distance Moduli, for Canonical and Revised p-Factor Laws

Cepheid	log P	$(m-M)_{0,\mathrm{ZAMS}}$	σ	$\Delta(m-M)_{0,\mathrm{old}}$	σ	$\Delta(m-M)_{0,\mathrm{new}}$	σ
CV Mon	0.730685	11.21	0.04	−0.21	0.05	−0.05	0.05
V Cen	0.739882	9.17	0.04	0.01	0.07	0.16	0.07
CS Vel	0.771201	12.59	0.14	−0.17	0.15	−0.02	0.15
U Sgr	0.828997	9.05	0.10	−0.21	0.10	−0.07	0.10
S Nor	0.989194	9.84	0.04	0.07	0.05	0.18	0.05
V340 Nor	1.052579	11.19	0.11	−0.04	0.21	0.06	0.21
X Cyg	1.214482	10.30	0.05	0.12	0.05	0.19	0.05
VY Car	1.276818	11.62	0.09	−0.12	0.09	−0.06	0.09
RZ Vel	1.309564	11.23	0.30	−0.21	0.30	−0.16	0.30
WZ Sgr	1.339443	11.27	0.04	0.02	0.06	0.06	0.06
SW Vel	1.370016	12.06	0.05	−0.07	0.06	−0.02	0.06
T Mon	1.431915	11.10	0.14	−0.29	0.15	−0.26	0.15

average more distant than the short-period ones. Since all the stars are relatively far away from the LMC bar, corrections of their distance moduli for the tilt of the LMC plane with respect to the line of sight are clearly important. We calculated these corrections from the geometrical model of the LMC of van der Marel & Cioni (2001); the values for the individual LMC Cepheids are given in the fifth column of Table 1. While the tilt corrections do alleviate the discrepancy between the distance moduli of the short- and long-period Cepheids, a significant slope on the distance moduli versus period plot remains. This is shown in Figure 9. The observed period dependence of the tilt-corrected LMC Cepheid distance moduli is clearly unphysical. While there is some scatter of the moduli to be expected for different reasons (see next section), there should clearly not exist a significant systematic trend with period. Figure 9 then suggests that there is a systematic problem with the ISB technique that introduces this observed period dependence. From all the sources of systematic and random uncertainty on the ISB distances that were discussed in detail in Gieren et al. (1997), there are only two sources of systematic error that can introduce such a period-dependent systematic effect on the distances calculated with the technique. These are (1) a wrong surface brightness–color relation and (2) a wrong conversion of radial velocity measurements to photospheric pulsational velocities.

In the discussion in the previous section, arguments were already given that the surface brightness–color relation in $V-K$ is now very accurately determined. The recent interferometric work on Cepheids has confirmed the FG97 relation at the 2% level. To see the effect of this small difference in the adopted surface brightness–color relation, we recalculated the distances of the 13 LMC Cepheids with the Kervella et al. (2004b) relation

$$F_v = -0.1336 \pm 0.0008(V-K)_0 + 3.9530 \pm 0.0006,$$

replacing the FG97 relation $[F_v = -0.131(V-K)_0 + 3.947]$. The result is that the LMC PL relation becomes very slightly *steeper* by this modification, increasing the discrepancy to the observed OGLE-II/Persson PL relations in the LMC even more and increasing the period dependence in the distance moduli seen in Figure 9. Adoption of the Kervella et al. (2004b) surface brightness–color relation therefore does not alleviate the period dependence in Figure 9 but rather works in the opposite direction. We therefore conclude that a wrong calibration of the Cepheid surface brightness–color relation can be excluded as the cause for the observed period dependence of the LMC distance moduli, at a very high level of confidence. We are then left with the p-factor. We therefore investigate a recalibration of the relation between p-factor and period sufficient to reconcile the short- and long-period Cepheid distances. We do this by (1) demanding that the period dependence of the distance moduli in Figure 9 disappears and (2) demanding that the mean difference between the observed ISB distances and ZAMS fitting distances to Galactic cluster Cepheids becomes zero, at the same time. The use of Galactic cluster Cepheids seems to be the most reasonable approach to fix the zero point of the p-factor law in a solid empirical way. To this end, we first have to select a sample of Galactic cluster Cepheids with both types of distance determination. After inspecting our Galactic Cepheid database in Storm et al. (2004), we found 12 cluster Cepheids having ISB distances, a high probability for cluster membership (e.g., Gieren & Fouqué 1993; Feast 1999; Turner & Burke 2002), and reasonably well determined ZAMS fitting distances. The ZAMS fitting distances to these 12 stars are given in Table 5 and were adopted from Sandage et al. (2004, hereafter STR04). They are based on a Pleiades distance modulus of 5.61, which is in excellent agreement with the recent results of Soderblom et al. (2005) based on *HST* astrometry of three Pleiades member stars (5.63 ± 0.02)

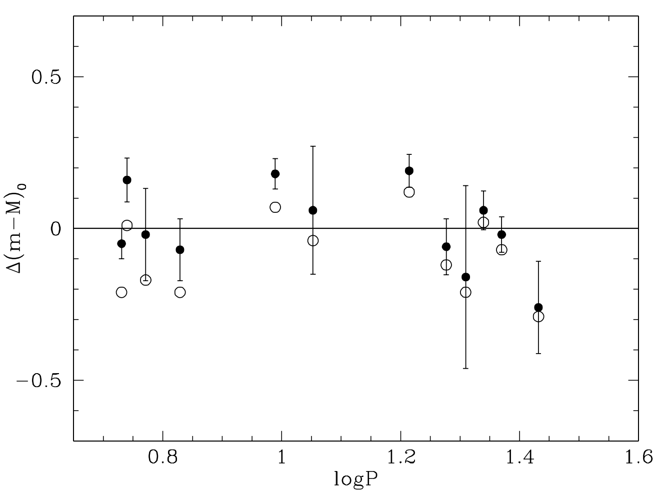

Fig. 10.—ISB and ZAMS fitting distance modulus difference, in the sense ISB − ZAMS, for the 12 open cluster Cepheids in Table 5, plotted against their period. *Open circles*: ISB distances have been calculated with the canonical p-factor law. *Filled circles*: ISB distances have been calculated with the revised p-factor law of this paper. Error bars have been plotted for the filled circles only and are the same for the open circles. Using the canonical p-factor law, the mean difference ISB − ZAMS is −0.09 mag. Using the revised p-factor law, the mean difference is zero.

TABLE 6
ISB LMC Cepheid Distance Moduli Assuming the Revised *p*-Factor Law

Cepheid	log *P*	$(m - M)_0$	$\sigma(m - M)$	Δm	$(m - M)_{0,\mathrm{LMC}}$
HV 12199	0.421469	18.545	0.094	−0.058	18.603
HV 12203	0.470427	18.683	0.092	−0.059	18.742
HV 12202	0.491519	18.486	0.072	−0.059	18.545
HV 12197	0.497456	18.362	0.058	−0.058	18.420
HV 12204	0.536402	18.392	0.044	−0.059	18.451
HV 12198	0.546887	18.502	0.028	−0.059	18.561
HV 12816	0.959466	18.444	0.087	−0.076	18.520
HV 12815	1.416910	18.328	0.028	−0.075	18.403
HV 899	1.492040	18.786	0.013	0.017	18.769
HV 879	1.566170	18.535	0.040	0.044	18.491
HV 909	1.574990	18.398	0.029	0.048	18.350
HV 2257	1.595150	18.786	0.028	0.054	18.732
HV 2338	1.625350	18.654	0.023	0.070	18.584

and of Percival et al. (2005) based on main-sequence fitting in the near-infrared (5.63 ± 0.05) and also consistent with the result of Southworth et al. (2005) from an analysis of the eclipsing binary HD 23642 in the Pleiades (5.72 ± 0.05). Since the STR04 paper does not state the uncertainties of the Cepheid ZAMS fitting distances, we adopted them from Turner & Burke (2002). The fifth column of Table 5 gives the differences of the ISB and ZAMS fitting moduli, in the sense ISB − ZAMS, while the sixth column gives the uncertainties of these differences, derived from a quadratic addition of the ISB and ZAMS fitting error bars. The mean difference between the ISB and ZAMS moduli is −0.09 mag. This is demonstrated in Figure 10, where we plot the distance modulus differences against the period of the Cepheids. The error bars in this diagram are dominated by the uncertainties of the ZAMS fitting distances.

While the period dependence of the *p*-factor law is basically determined by the observed trend in Figure 9 and its zero point by the mean deviation of the cluster Cepheid ZAMS fitting distances from their ISB distances, the determination of both constants in the *p*-factor law is not orthogonal. After several iterations, we determined as our best *revised p*-factor law from our adopted approach the following relation:

$$p = 1.58(\pm 0.02) - 0.15(\pm 0.05) \log P,$$

where the uncertainties of the coefficients were derived from the observed scatter in Figures 9 and 10. Recalculating the ISB distances of the cluster Cepheids in Table 5 with this revised *p*-factor law, the average difference of (ISB − ZAMS) moduli now becomes zero (seventh column of Table 5); this is demonstrated in Figure 10 (*filled circles*). It is also evident from this figure that the modification of the *p*-factor law has not introduced any significant trend of the (ISB − ZAMS) modulus differences with period, which would hint at a problem with the newly determined period dependence in this relation. In Table 6 we present the revised distance moduli for the 13 LMC Cepheids calculated with the new *p*-factor law. Correcting them for the tilt of the LMC bar, we obtain the values in the last column of this table. Plotting the distance moduli against the pulsation period in Figure 11 demonstrates that the adoption of the revised *p*-factor law in the calculation of the ISB distances has effectively removed any dependence of the LMC Cepheid tilt-corrected true distance moduli on period, confirming that the revised *p*-factor law both eliminates the period dependence of the ISB-calculated LMC Cepheid distance moduli and at the same time produces full consistency between the set of ISB and ZAMS fitting distances to the Galactic cluster Cepheids, without introducing any significant trend of the distance differences in Figure 10 with period.

What is the effect of this recalibration of the *p*-factor law on the PL relations obtained from the ISB technique in both the LMC and the Milky Way? To this end, we recalculated the ISB distances of all Milky Way and LMC Cepheids with the new *p*-factor law, keeping everything else as in the original distance calculations that produced the PL relations in Figures 3–7. The revised ISB distances of the Galactic Cepheids and the resulting absolute magnitudes in the different photometric bands are given in Table 7, which also gives the revised radii of the stars that will be discussed elsewhere. In Table 7 we have added four Cepheids to the list of Storm et al. (2004); the data sources we have adopted for these additional objects are given in Table 8. The modified PL relations now all turn out to be shallower. While the Milky Way and LMC Cepheid PL relations from the ISB technique remain nearly identical to each other in all bands, they are now much closer to the observed OGLE-II/Persson LMC relations. The slopes of the PL relations in the LMC and Milky Way obtained with the revised *p*-factor law are given in Table 9, and in Figures 12 and 13 we show the modified PL relations in

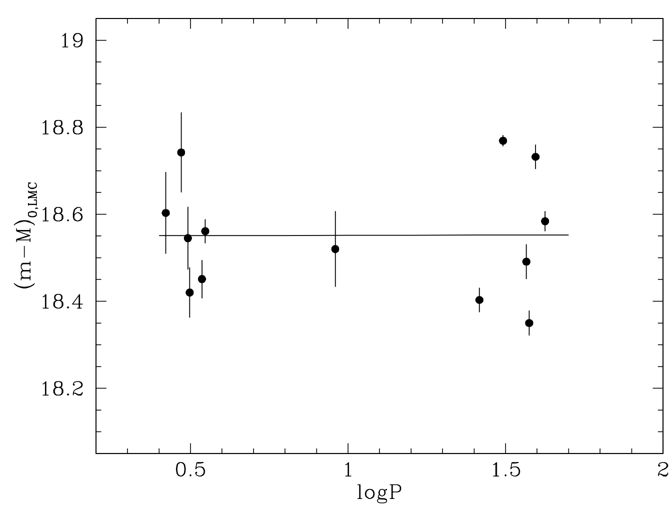

Fig. 11.—True distance moduli of the LMC Cepheids from their ISB distances, now calculated with the revised *p*-factor law derived in this paper. There is no trend with period anymore. The LMC barycenter distance from these data is 18.56 ± 0.04 mag.

TABLE 7

Revised Galactic Cepheid ISB Distances, Radii, and Absolute Magnitudes Assuming the Revised p-Factor Law

Cepheid	log P	$(m-M)_0$	$\sigma_{(m-M)}$	R	σ_R	M_B	M_V	M_I	M_J	M_H	M_K	M_W	$E(B-V)$	$\Delta\phi$
SU Cas	0.289884	8.399	0.070	32.7	1.0	−2.960	−3.375	−3.876	−4.160	−4.347	−4.372	−4.632	0.287	0.000
EV Sct	0.490098	11.448	0.105	37.4	1.8	−3.078	−3.543	−4.177	−4.429	−4.617	−4.640	−5.133	0.679	0.045
BF Oph	0.609329	9.448	0.034	34.7	0.5	−2.312	−2.928	−3.576	−4.021	−4.290	−4.359	−4.554	0.247	0.035
T Vel	0.666501	9.970	0.060	36.3	1.0	−2.216	−2.860	−3.537	−4.055	−4.347	−4.428	−4.559	0.281	0.000
δ Cep	0.729678	7.242	0.044	45.1	0.9	−3.027	−3.588	−4.217	−4.628	−4.909	−4.965	−5.166	0.092	0.000
CV Mon	0.730685	11.159	0.034	43.7	0.7	−2.627	−3.207	−3.965	−4.434	−4.718	−4.819	−5.110	0.714	0.015
V Cen	0.739882	9.330	0.063	45.1	1.3	−2.869	−3.450	−4.112	−4.569	−4.849	−4.925	−5.111	0.289	0.000
CS Vel	0.771201	12.567	0.064	41.3	1.2	−3.161	−3.661	−4.185	−4.539	−4.766	−4.827	−4.977	0.847	0.000
BB Sgr	0.821971	9.660	0.028	53.2	0.7	−2.958	−3.659	−4.403	−4.865	−5.170	−5.243	−5.527	0.284	−0.035
U Sgr	0.828997	8.977	0.021	50.8	0.5	−2.925	−3.617	−4.353	−4.808	−5.090	−5.163	−5.463	0.403	0.000
η Aql	0.855930	7.125	0.045	51.5	1.1	−3.081	−3.716	−4.406	−4.852	−5.147	−5.208	−5.448	0.149	0.000
S Sge	0.923352	9.334	0.035	62.5	1.0	−3.456	−4.136	−4.812	−5.276	−5.566	−5.628	−5.834	0.127	0.000
S Nor	0.989194	10.020	0.032	74.4	1.1	−3.457	−4.213	−4.968	−5.523	−5.846	−5.930	−6.108	0.189	0.000
Z Lac	1.036854	11.549	0.043	74.8	1.5	−3.773	−4.468	−5.205	−5.625	−5.939	−6.002	−6.319	0.404	0.000
XX Cen	1.039548	11.216	0.022	72.7	0.8	−3.532	−4.256	−4.999	−5.517	−5.821	−5.904	−6.121	0.260	−0.040
V340 Nor	1.052579	11.246	0.185	70.3	6.0	−3.085	−3.914	−4.779	−5.326	−5.678	−5.770	−6.085	0.315	0.000
UU Mus	1.065819	12.687	0.084	77.4	3.0	−3.526	−4.256	−5.022	−5.592	−5.910	−6.002	−6.178	0.413	−0.005
U Nor	1.101875	10.806	0.060	79.5	2.2	−3.804	−4.506	−5.232	−5.735	−6.018	−6.108	−6.329	0.892	0.000
BN Pup	1.135867	13.035	0.050	86.6	2.0	−3.848	−4.597	−5.353	−5.864	−6.184	−6.266	−6.495	0.438	0.000
LS Pup	1.150646	13.636	0.056	93.6	2.4	−4.008	−4.767	−5.515	−6.035	−6.363	−6.439	−6.643	0.478	0.000
VW Cen	1.177138	12.881	0.039	89.8	1.6	−3.224	−4.114	−5.005	−5.707	−6.099	−6.213	−6.351	0.448	0.000
X Cyg	1.214482	10.489	0.018	109.0	0.9	−4.192	−5.060	−5.837	−6.342	−6.684	−6.760	−7.010	0.288	0.000
Y Oph	1.233609	8.934	0.029	92.3	1.2	−4.215	−4.925	−5.718	−6.132	−6.394	−6.458	−6.916	0.655	0.000
VY Car	1.276818	11.556	0.022	115.8	1.2	−3.986	−4.903	−5.759	−6.381	−6.736	−6.840	−7.053	0.243	−0.020
RY Sco	1.307927	10.567	0.034	102.4	1.6	−4.447	−5.113	−5.859	−6.322	−6.593	−6.676	−6.985	0.777	0.000
RZ Vel	1.309564	11.073	0.029	117.6	1.6	−4.301	−5.093	−5.877	−6.460	−6.787	−6.878	−7.060	0.335	0.000
WZ Sgr	1.339443	11.334	0.047	124.4	2.7	−3.921	−4.848	−5.768	−6.428	−6.812	−6.928	−7.157	0.467	0.000
WZ Car	1.361977	12.961	0.066	114.3	3.5	−4.184	−4.960	−5.760	−6.365	−6.704	−6.787	−6.967	0.384	0.000
VZ Pup	1.364945	13.122	0.056	98.8	2.6	−4.362	−5.050	−5.762	−6.231	−6.533	−6.594	−6.836	0.471	0.000
SW Vel	1.370016	12.036	0.025	119.5	1.4	−4.252	−5.060	−5.885	−6.485	−6.827	−6.931	−7.132	0.349	−0.020
T Mon	1.431915	10.844	0.055	151.6	3.9	−4.432	−5.401	−6.276	−6.921	−7.303	−7.404	−7.598	0.209	0.000
RY Vel	1.449158	12.045	0.032	141.5	2.1	−4.719	−5.527	−6.328	−6.911	−7.209	−7.303	−7.538	0.562	−0.005
AQ Pup	1.478624	12.542	0.045	149.2	3.1	−4.669	−5.533	−6.427	−6.969	−7.321	−7.423	−7.778	0.512	−0.055
KN Cen	1.531857	13.134	0.045	186.7	3.9	−5.652	−6.338	−6.985	−7.516	−7.846	−7.946	−7.962	0.926	0.005
l Car	1.550816	8.749	0.022	179.5	1.8	−4.471	−5.581	−6.530	−7.214	−7.631	−7.721	−7.963	0.170	−0.040
U Car	1.588970	10.909	0.025	157.5	1.9	−4.658	−5.551	−6.416	−7.038	−7.387	−7.488	−7.722	0.283	−0.050
RS Pup	1.617420	11.556	0.064	207.5	6.1	−5.041	−6.009	−6.956	−7.594	−7.962	−8.078	−8.386	0.446	0.000
SV Vul	1.653162	12.088	0.037	222.6	3.8	−5.862	−6.738	−7.553	−7.987	−8.300	−8.359	−8.783	0.570	−0.045

TABLE 8

References to the Papers Containing the Observational Data for the Four Stars that Have Been Added to the Sample of Storm et al. (2004) and the New Radial Velocity Data for l Car

Star	Optical Photometry	Infrared Photometry	Radial Velocity
CS Vel.......	1	2, 3, 4	5, 6
S Sge.........	7, 8, 9	4, 8	10
Z Lac.........	7, 8	8	11, 12
Y Oph	7, 13, 14	2, 4	10
l Car			15

References.—(1) Berdnikov & Turner 1995; (2) Laney & Stobie 1992; (3) Schechter et al. 1992; (4) Welch et al. 1984; (5) Bersier et al. 1994; (6) Metzger et al. 1992; (7) Moffet & Barnes 1984; (8) Barnes et al. 1997; (9) Kiss 1998; (10) Gorynya et al. 1998; (11) Sugars & Evans 1996; (12) Imbert 1996; (13) Pel 1976; (14) Coulson & Caldwell 1985; (15) Taylor et al. 1997.

the *K* and *W* bands, respectively, where any remaining effect of reddening on the absolute magnitudes is basically negligible. It is seen that the change of the *p*-factor law not only has reconciled the distance moduli of the short- and long-period LMC Cepheids but has at the same time brought about very good agreement of the ISB PL relation (in all bands) in the LMC with the observed OGLE-II/Persson relations (at the combined 1 σ levels). It is also seen that the Milky Way PL relation slopes are now in very good agreement, again at the combined 1 σ level, with the slopes of the PL relations in the LMC, in all bands. As the principal result of this discussion, we then find that, from the requirement that the distance moduli of the LMC Cepheids cannot depend in a systematic way on their periods, we obtain, as a direct consequence, PL relations for both the LMC and the Milky Way whose slopes agree very well with those of the directly observed and extremely well established PL relations in the LMC.

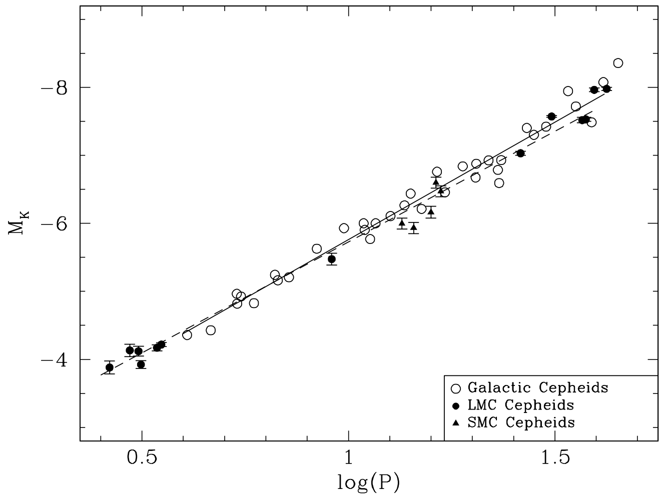

Fig. 12.—Absolute magnitudes in the *K* band from the ISB distances of Milky Way, LMC, and SMC Cepheids, all calculated with the revised *p*-factor law of this paper. The solid line is the best fit to the Milky Way Cepheid data. The dashed line is the Persson et al. (2004) *K*-band PL relation for the LMC, for an assumed LMC distance modulus of 18.50. The slopes of the PL relations for both the LMC and Milky Way derived from the ISB technique agree now very well with the slope of the observed *K*-band relation in the LMC. The slight mean offset of the five SMC Cepheids from the Galactic relation has been used by Storm et al. (2004) to constrain the metallicity effect on the zero point of the PL relation.

5. DISCUSSION

The conclusions in the previous section were based on the observed period dependence of the tilt-corrected distance moduli of the LMC Cepheids, as shown in Figure 9. Beyond the significant systematic trend of the distance moduli with period, there is some appreciable scatter of the data in this diagram and in the corrected diagram in Figure 12. Since the ISB distance moduli are very insensitive to reddening and to metallicity differences among the Cepheids (Welch 1994; Gieren et al. 1998; Storm et al. 2004), slight errors in the reddenings we used, or the modest differences between the individual metallicities of the Cepheids (see data in Table 3), are not expected to produce any significant dispersion in Figures 9 and 11. One of the factors that can introduce some significant random scatter in the ISB distance moduli is the size of the amplitudes of the respective $V-K$ color curves of the Cepheids (Gieren et al. 1997). The random spread among the distance moduli of the short-period Cepheids in our sample, which are all members of the same cluster and therefore all at the same distance, is probably mainly a consequence of their relatively small color amplitudes. It is more difficult to understand the observed spread among the distance moduli of the long-period stars in our sample. The $V-K$ amplitude-related random errors are expected to be quite small for these stars (with the exception of HV 12816, which has a low color amplitude, too), as indicated by the error bars in Figures 9 and 11. A depth effect, in the sense that some of these Cepheids might be significantly closer or more distant than the LMC plane, could contribute to the observed scatter, but this seems unlikely given the young age of these stars, which clearly favors their location in or very close to the LMC disk. An effect that will contribute to some degree to the random scatter among the distance moduli of all Cepheids, independent of their periods, is the values of the adopted phase shifts between the angular and linear displacement curves in the ISB solutions. In our previous papers we have shown that the change of the distance modulus of a given Cepheid for any reasonable variation of its appropriate phase shift is quite small, if the data sets are of high quality, as is the case for all of our current stars. For none of the Cepheids in this study would a maximum change of its adopted phase shift still compatible with the data alter its distance modulus by more than ~0.06 mag. It therefore seems difficult to understand the observed random spread among the long-period Cepheid moduli without invoking a depth effect to some degree, or some additional source of random uncertainty we have not identified so far.

TABLE 9

Slopes of the Period-Luminosity Relation from the ISB Technique Assuming the Revised *p*-Factor Law

Band	LMC	σ	Milky Way	σ	LMC (OGLE-II/Persson)	σ
V..........................	−2.867	0.093	−2.898	0.133	−2.775	0.031
I...........................	−3.108	0.079	−3.129	0.109	−2.977	0.021
W..........................	−3.469	0.074	−3.477	0.100	−3.300	0.011
J...........................	−3.295	0.078	−3.328	0.095	−3.153	0.051
K..........................	−3.359	0.072	−3.456	0.097	−3.261	0.042

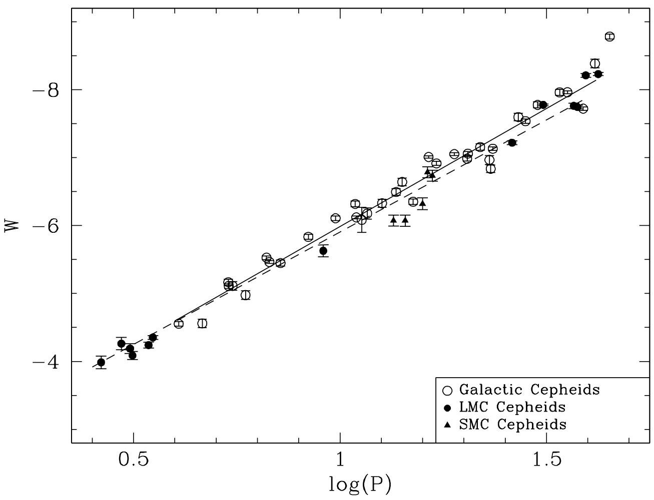

Fig. 13.—Absolute Wesenheit magnitudes, calculated with the revised *p*-factor law. The solid line is the best fit to the Milky Way Cepheid data. The dashed line is the OGLE-II relation observed for the LMC, for an assumed LMC distance modulus of 18.50. The slopes of the *W*-band PL relations for both the LMC and Milky Way from the ISB technique agree now very well with the observed *W*-band relation in the LMC.

A possible weakness in our current interpretation of the LMC ISB distance data is the fact that all the short-period stars are situated in the cluster NGC 1866. It is not a priori excluded that NGC 1866 may lie closer to us than the LMC main body and that therefore the smaller distance moduli of the NGC 1866 Cepheids in Figure 9 are true and not caused by a wrong *p*-factor applied to these stars. Indeed, Walker et al. (2001) found from ZAMS fitting to the cluster color-magnitude diagram obtained from *HST* data a true distance modulus of 18.35 ± 0.05 mag and a reddening of 0.06 mag, consistent with the canonical reddening value for the cluster used in all previous work (see Storm et al. 2005). This value is in conflict, however, with the distance derived from red clump stars in a field around the cluster, which is 18.53 ± 0.07 mag (Salaris et al. 2003). More recently, Groenewegen & Salaris (2003) used the Cepheid population of NGC 1866, including the six Cepheids used in our present paper, to demonstrate that the reddening-free Wesenheit magnitudes of the NGC 1866 Cepheids are consistent with a distance difference of 0.04 ± 0.03 mag between the cluster and the LMC disk, in the sense that the cluster is *more distant* than the LMC main body by this amount. The smallness of this difference supports the idea that NGC 1866 is very close to, or located in, the LMC main body, in agreement with the result coming from the surrounding red clump star population. The relatively young age of NGC 1866 of $\log t \sim 8.0$ yr from the theoretical pulsational period–age relation applied to its Cepheids (Bono et al. 2005), consistent with its evolutionary age, would also make us expect that the cluster is located in the LMC main body where most of the recent star formation in the LMC has taken place. In their study, Groenewegen & Salaris (2003) also found evidence that the reddening of NGC 1866 is actually somewhat higher [$E(B-V) = 0.12$ mag] than the canonical value and show that the ZAMS fitting distance to NGC 1866 can be reconciled with the distance derived from the cluster Cepheids and surrounding field red clump stars under the assumption that the higher reddening value is correct. Such a higher reddening of the NGC 1866 stars, if true, would not affect our present ISB distance determination for them in any significant way, and it would also not significantly affect the LMC PL relations of this paper in the reddening-insensitive *W* and *K* bands and would therefore not alter the principal conclusions of our paper. However, it is clear from the previous discussion that it is very desirable to determine ISB distances for a number of additional short-period Cepheids in the LMC that belong to the general field population, and not to just one cluster, in order to make our conclusions invulnerable to the possibility that the cluster could be located in front of or behind the LMC plane by a significant amount.

From the tilt-corrected distance moduli of our LMC Cepheid sample as given in the last column of Table 6, we derive a true LMC barycenter distance modulus of 18.56 ± 0.04 mag. To this random uncertainty derived just from the scatter of the individual LMC Cepheid distance moduli, we should add a systematic uncertainty that will affect the LMC distance result via the dependence of the adopted zero point in the *p*-factor law on the adopted ZAMS fitting moduli of the Galactic cluster Cepheids in Table 5. This systematic uncertainty is difficult to estimate but should not exceed 0.1 mag, given that the very recent work on the Pleiades distance cited before has considerably reduced the uncertainty on this number, to which the adopted ZAMS fitting moduli of the Cepheids in Table 5 are tied. As a conservative estimate, we therefore find from this work that $(m-M)_0(\mathrm{LMC}) = 18.56$ mag, with a 0.04 mag random and a $\sim$0.1 mag systematic uncertainty. This value is in good agreement with the "canonical" LMC distance value preferred by the *HST* Key Project on the Extragalactic Distance Scale (Freedman et al. 2001). We expect that once accurate model results on the *p*-factor law become available, we will be able to reduce the current systematic uncertainty on the LMC distance from the ISB technique by tying our zero point to the models, rather than to the ZAMS fitting scale, as we did in our previous surface brightness distance work.

STR04 have recently analyzed Cepheid data in the LMC and have found marginal evidence for a break in the LMC PL relation at a period of 10 days, in the sense that Cepheids with $P < 10$ days define steeper PL relations than those with $P > 10$ days. Since the OGLE-II sample contains only very few long-period Cepheids, STR04 had to enhance the OGLE-II sample with 97 long-period Cepheids whose data were taken from a variety of sources, in order to obtain acceptable statistics in their fits. This has made their conclusions vulnerable, however, to all the problems one can have when combining photometric data sets in crowded fields from different sources, where differences up to 0.1 mag for the magnitudes of the same stars are no exception. We therefore believe that the claim of STR04, extremely important if true, has to be checked with independent high-quality photometry of Cepheids of *all* periods in the LMC, up to the largest observed ones, obtained in a very homogeneous way. Some of the authors are currently engaged in such a new observational program that will provide very accurate Cepheid mean magnitudes in *V* and *I* for many hundreds of variables up to periods of at least 80 days, which will be discovered in fields in or close to the LMC bar. This homogeneous and statistically significant data set will definitively prove or disprove the claim about a period break in the LMC PL relation. From the observational data currently at hand, and in particular from the extremely homogeneous OGLE-II database alone, the Cepheid data seem consistent, at a high level of confidence, with no break of the PL slope at 10 days or some other period. However, as said before, this conclusion must be checked with homogeneous photometric data on many more long-period Cepheids. Our current ISB distance determinations of 13 LMC Cepheids are certainly fully consistent with no period break in the PL relation, but of course we would not see such a subtle effect from our current small sample.

6. CONCLUSIONS

The derivation of direct distances to 13 LMC Cepheids with the ISB technique has revealed a period-dependent and significant discrepancy between the individual distance moduli, while at the same time the PL relations in the LMC from the ISB technique agree exceedingly well with the corresponding Milky Way Cepheid relations found in Storm et al. (2004). Given the existing very accurate interferometric calibration of the Cepheid surface brightness–color relation for the V, $V - K$ magnitude/color combination we are using in our distance analyses and the resulting accurate determination of the angular diameter curves of our program Cepheids in the LMC, we identify as the most likely culprit of the period dependence seen in the $(m - M)_0$–period diagram a systematic error in the determination of the linear displacement curves of the Cepheids from their observed radial velocity curves. The problem is likely due to a flawed calibration of the period dependence of the p-factor that provides the transformation of the observed radial velocities to the pulsational velocities of the Cepheids. We find that, assuming a steeper period dependence of the p-factor law, we can reconcile, within the current uncertainties, the distance moduli of the individual LMC Cepheids (after correcting them for the tilt of the LMC plane with respect to the line of sight with the geometrical model of van der Marel & Cioni 2001) and the slopes of the LMC period-luminosity relations, which, using the revised p-factor law we derive in this study, agree to within the combined 1 σ uncertainties with the PL relations observed in the LMC by the OGLE-II Project and by Persson et al. (2004) in the near-infrared. When we recalculate the ISB distances of the Milky Way Cepheids with the revised p-factor relation, we obtain excellent consistency of the slopes of the Galactic Cepheid PL relations in all optical and near-infrared bands and the corresponding LMC PL relations derived from the ISB technique, which all agree within $\pm 1\ \sigma$ with the directly observed and extremely well established LMC PL relations in *VIWJK*. Tying the zero point of our new p-factor law calibration to a sample of well-established Galactic cluster Cepheids, we find from our 13 LMC Cepheid sample a true distance modulus of the LMC barycenter of 18.56, with an estimated 0.04 mag random and 0.1 mag systematic uncertainty, in very good agreement with the "canonical" LMC distance adopted by the *HST* Key Project team. We believe that taking all this information together, there is now strong empirical evidence that our conclusions regarding the need of revision of the p-factor law are correct. Evidently, we will be able to calibrate the period dependence of the p-factor more accurately once we can obtain ISB distance determinations for a larger sample of LMC Cepheids. A program to obtain the necessary data, particularly high-quality radial velocity curves of selected Cepheids, has very recently been started. It should be noted, however, that the current sample is already providing relatively accurate information on the period dependence of the p-factor because of the concentration of the Cepheids toward short and long periods. With the extended sample, we will fill in intermediate periods and at the same time increase the number of Cepheids with very short and very long periods.

In spite of the evidence for a need of revision of the p-factor law presented in this paper, there are several aspects that will need further work, to definitively prove or disprove our conclusions. First, there is evidently a need to reproduce the "observed" p-factor law from new and refined models of Cepheid atmospheres. Past work, as that of Sabbey et al. (1995), has perhaps concentrated too much on fixing the zero point of the law and the possible variation of p during the pulsation cycle of a Cepheid, and less on establishing its systematic dependence on the stellar luminosity and effective temperature and thus on the period. Our group (Gieren et al. 1993) was the first to recognize that the models of Hindsley & Bell (1986) actually predicted such a systematic period dependence, and the current results of this paper at least confirm the sign of this trend (e.g., p becomes smaller with increasing pulsation period). Given the relatively small amount of past theoretical work invested in this problem, it is perhaps not surprising that we find a rather strong disagreement with the observations. We also note that this discovery would not have been possible with the study of Galactic Cepheids alone: as in the discovery of the PL relation 100 years ago, we needed to study a sample of Cepheids all lying at the same distance and still being bright enough for accurate work, and the LMC remains the ideal place for such a study. Yet, we cannot be completely sure if our current interpretation of the data is correct as long as the suggested period dependence of the p-factor is not physically understood from better models. We hope that our current results will spur new investigations in this field. Another point that needs to be improved is the inclusion of additional short-period LMC Cepheids in our analysis that are not all members of a given cluster, as the ones we had available for the current analysis. While we have presented arguments that in our belief support that these Cepheids and their host cluster are actually located very close to or in the LMC bar, it remains a cause of concern that NGC 1866 could be located in front of the LMC bar by a significant amount, which would alter the value of the slope of the p-factor law we derive from the data in Figure 9 and, consequently, the slopes of the PL relations in Table 9. The acquisition of new data for the ISB analyses of such additional short-period LMC field Cepheids is underway and should help to clarify this question.

With these caveats in mind, our current results support the evidence that the slope of the Cepheid PL relation, at least in the optical V, I, and W bands, does not vary significantly with metallicity between -1.0 dex and solar metallicity. Udalski et al. (2001) demonstrated that in the metal-poor galaxy IC 1613 the PL slopes agree very well with the LMC slopes, and the same group established in the OGLE-II project that there is no measurable difference between the PL relation slopes in the LMC and SMC (at -0.7 dex) either. Recently, Gieren et al. (2004) and Pietrzyński et al. (2004) have shown that the observed PL relations in *VIW* in NGC 300 and NGC 6822 are also extremely well fitted by the respective OGLE-II LMC slope, NGC 300 and NGC 6822 having mean metallicities of their young stellar populations of about -0.3 (Urbaneja et al. 2005) and -0.5 dex (Venn et al. 2001), respectively. The previous indications that the slope of the PL relation in the solar-metallicity Milky Way might be steeper than in the more metal-poor systems were mostly based on the results of the distance determinations with the ISB technique. We have shown in this paper that there is a high probability that these conclusions were flawed, due to the incorrect theoretical calibration of the canonical p-factor law. If substantiated by future theoretical and improved empirical work, this would be obviously very good news for the use of the Cepheid PL relation as a primary distance indicator and would eliminate a strong concern that has been with us for a number of years.

Regarding the slopes of the near-infrared Cepheid PL relations, particularly the K-band relation, which is potentially the most accurate means to determine Cepheid-based distances to galaxies due to its insensitivity to absorption corrections and its small intrinsic dispersion as compared to optical PL relations (as recently impressively demonstrated by the work of Persson et al. 2004), we can now say that the present study suggests that the Milky Way relation agrees in slope with the observed LMC relation to within 1 σ, providing evidence for no change of the slope in the metallicity regime from -0.3 dex to solar either. Very recent empirical results on the Cepheid *K*-band PL relation in NGC 300 (Gieren et al. 2005) also indicate excellent agreement with the LMC PL relation in *K* of Persson et al. (2004), strengthening the evidence that the slope of the *K*-band PL relation is metallicity independent as well. However, the *K*-band PL relation has yet to be studied for more metal-poor galaxies to confirm this.

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