New period-luminosity and period-color relations of classical Cepheids

IV. The low-metallicity galaxies IC 1613, WLM, Pegasus, Sextans A and B, and Leo A in comparison to SMC

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ABSTRACT

The metal-poor, fundamental-mode (P0) and first-overtone (P1) Cepheids in the dwarf galaxies IC 1613, WLM, Pegasus, Sextans A, Sextans B, and Leo A are compared with the about equally metal-poor Cepheids of the Small Magellanic Cloud (SMC). The period-color (P-C) and period-luminosity (P-L) relations of the seven galaxies are indistinguishable, but differ distinctly from those in the Large Magellanic Cloud (LMC) and the solar neighborhood. Adopting $(m - M)^0_{SMC} = 18.93$ from independent evidence, one can determine reliable distance moduli for the other dwarf galaxies of $(m - M)^0 = 24.34 \pm 0.03, 24.95 \pm 0.03, 24.87 \pm 0.06, 25.60 \pm 0.03$ (mean for Sextans A & B), and 24.59 ± 0.03, respectively.

Key words. stars: variables: Cepheids – distance scale

1. Introduction

It has been shown that the character of the period-luminosity (P-L) relations varies particularly at short wavelengths as a function of the metallicity (Sandage et al. 2009, in the following Paper III). This implies the *prediction* that the very low-metallicity Cepheids in IC 1613, WLM, and the Pegasus dwarf system should follow P-L relations that are more similar to those of the SMC than those defined by the more metal-rich Cepheids in the LMC and the Galaxy. The same prediction holds for the period-color (P-C) relations. The purpose of this paper is therefore to compare the P-L and P-C relations of the three above-mentioned galaxies with the corresponding, well-defined relations of the SMC (Paper III, but revised here in Sect. 2). Fundamental-mode (P0) as well as first-overtone (P1) Cepheids are considered.

In addition, we consider the Cepheids in Sextans A and Sextans B (joined here into one set) and in Leo A. The metallicity of the young population in these galaxies is still lower by a factor of three to four than in SMC. The question is whether this additional underabundance has a noticeable effect on the P-L and P-C relations.

The most metal-poor galaxy known, i.e. I ZW 18 with $[O/H]_{T_e} = 7.2$ (Skillman & Kennicutt 1993), is not considered here because so far only a single Cepheid is known in the useful period range (Fiorentino et al. 2010).

The metallicities in the T_e-based system of Zaritsky et al. (1994) of the galaxies in the present sample and their Galactic foreground reddenings (from Schlegel et al. 1998) are given in Table 1. All data are corrected in the following for foreground reddening and absorption.

The P-C and P-L relations of the P0 and P1 Cepheids in the five sample galaxies and their distances are discussed in Sects. 3–7. The mean P0 and P1 distances are discussed in the light of independent distance determinations in Sect. 8. In Sect. 9, we compare the P-C and P-L relations of the metal-poor sample galaxies with the corresponding relations for more metal-rich Cepheids.

2. The P-C and P-L relations of SMC as templets for fundamental-mode (P0) and first-overtone (P1) pulsators

The P-C and P-L relations of the P0 Cepheids in SMC were derived in Paper III using the B, V, I photometry of the OGLE program (Udalski et al. 1999b). Following common practice, the Cepheids with $\log P < 0.4$ were excluded. The remaining about 450 Cepheids are individually corrected for internal absorption by Udalski et al. By performing fits to the data, we were unable to unambiguously decide whether the relations have a break at $\log P = 1.0$ as in LMC or not. The (P-C) relation in $(B-V)$ showed the break clearly, whereas in $(V-I)$ and the P-L relations it remained insignificant.
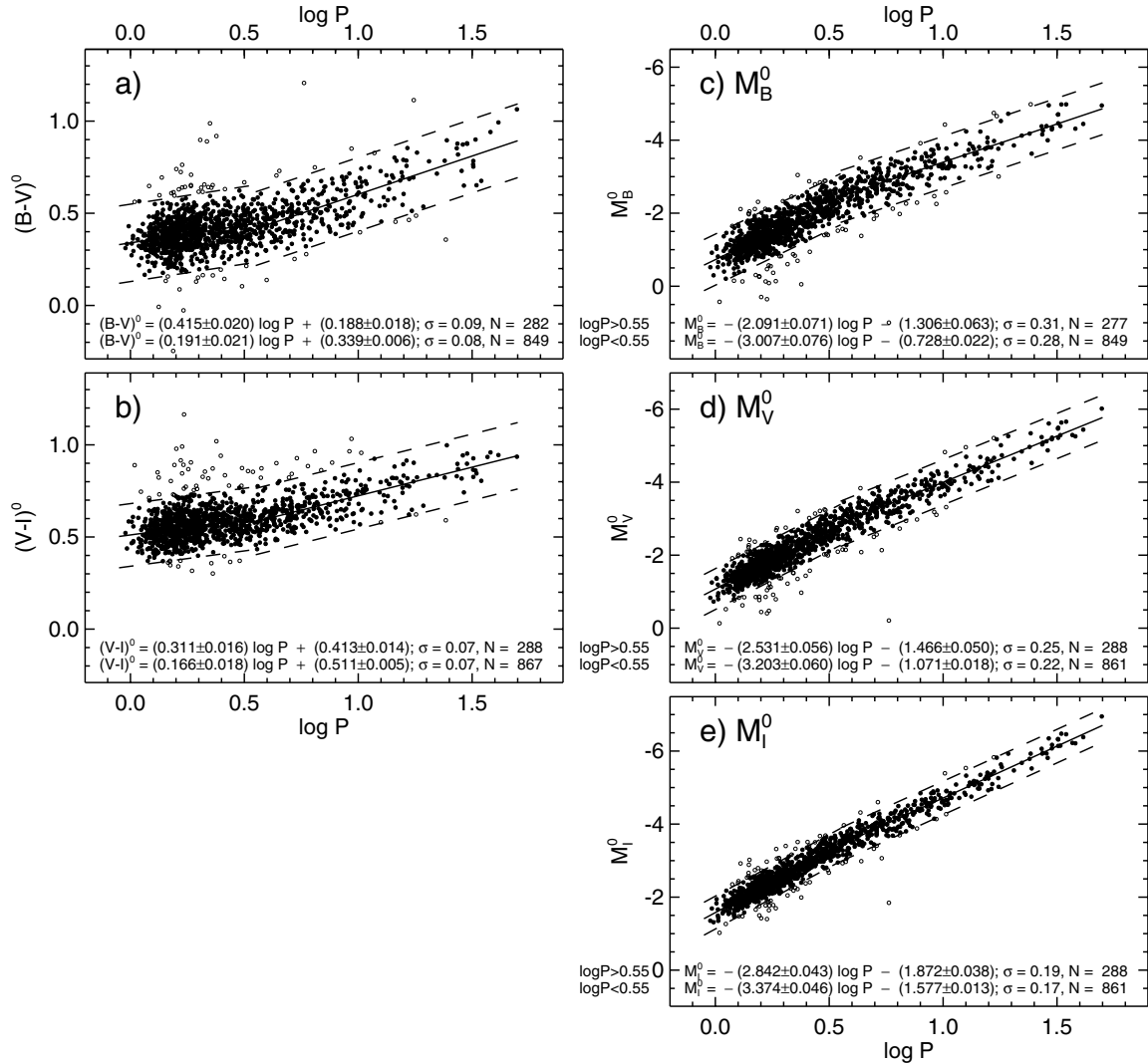
The analysis is repeated here by fitting two linear regressions to the total of about 1100 P0 Cepheids (including $\log P < 0.4$) and treating the position of the break as a free parameter. The additional requirement is a minimum discontinuity of the P-C and P-L relations at the break period. Higher-order regressions are, of course, possible, but the linear fits are adequate for all practical purposes and facilitate the comparison with other galaxies.

In addition, the corresponding relations in $(B-V)$, $(V-I)$, and B, V, and I are derived in Sect. 2.2 also for the P1 Cepheids of SMC as identified by Udalski et al. (1999b).

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Table 1. Metallicities and foreground reddening of the sample galaxies.

	$[O/H]_{T_e}$	Source	$E(B-V)_{Gal}$
SMC	7.98	Sakai et al. (2004)	variable
IC 1613	7.86	Sakai et al. (2004)	0.025
WLM	7.74	Sakai et al. (2004)	0.037
Pegasus	7.92	Skillman et al. (1997)	0.066
Sex A & B	7.52	Skillman et al. (1989)	0.044, 0.032
Leo A	7.38	(Skillman et al. 1989; van Zee et al. 2006)	0.021

Fig. 1. The revised P-C and P-L relations of the P0 Cepheids of SMC including the shortest-periods and with the adopted break at $\log P = 0.55$. The dashed lines are the 2σ boundaries; objects outside are excluded. **a), b)** The P-C relations in $(B-V)$ and $(V-I)$, respectively. **c)–e)** The P-L relations in B, V, and I, respectively.

The very large set of SMC Cepheids with V and I photometry by Soszyński et al. (2010) defines P-C and P-L relations whose slopes agree with the ones derived here, but the magnitudes are not corrected for variable internal absorption. Therefore, the data were not used here.

2.1. Fundamental-mode (P0) P-C and P-L relations of SMC

The P-C relations in $(B-V)$ and $(V-I)$ of the P0 Cepheids of SMC are shown in Figs. 1a and b. They are well-defined for

Cepheids with about $0.0 < \log P < 1.5$ and show a striking break near $\log P = 0.55$. At this point, the two regressions merge into each other with little discontinuity. The remaining mismatch is smaller than the statistical errors of the two segments.

The P-L relations in B, V, and I are shown in Figs. 1c to e. Their highly significant break is found near $\log P = 0.55$ in agreement with the P-C relations. For the calibration of the P-L relations, the distance of SMC of $(m-M)^0_{SMC} = 18.93$ is adopted from Tammann et al. (2008a, hereafter TSR 08a, Table 7). This value with an estimated uncertainty of <0.1 mag is the mean of
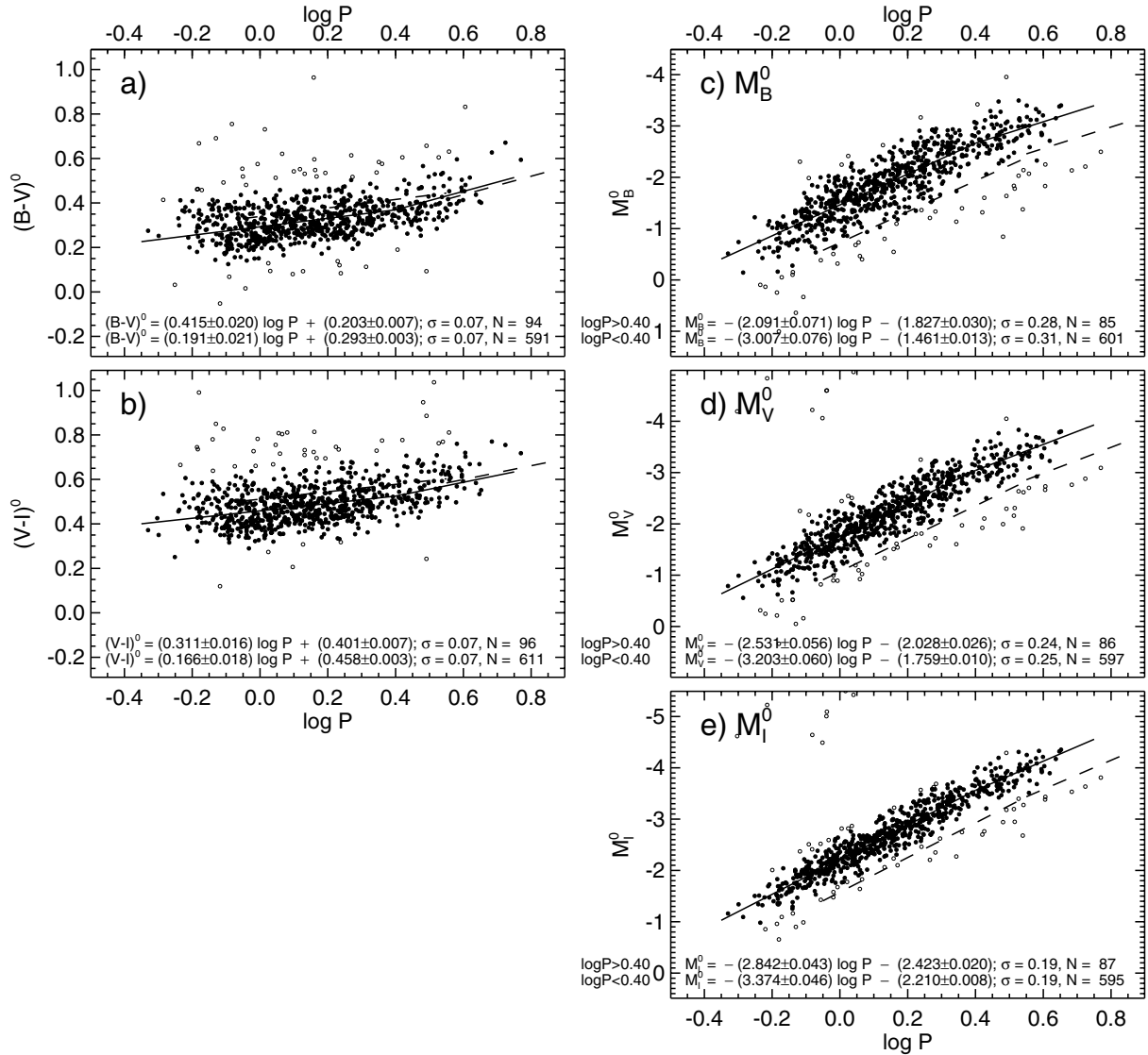
Fig. 2. The P-C and P-L relations of the P1 Cepheids of SMC with the adopted break at $\log P = 0.4$. The dashed lines show the locus of the P0 Cepheids.

different distance determinations, but is *independent* of the P-L relation of Cepheids. All distances in this paper are based on this zero-point.

The equations of the P-C and P-L relations, after 2σ clipping, are shown at the bottom of the respective panels in Fig. 1 for the Cepheids below and above the break point; they are repeated in Table 5 below.

2.2. First-overtone (P1) P-C and P-L relations of SMC

The P1 Cepheids of SMC span an interval of $-0.3 < \log P < 0.6$. They were identified as P1 pulsators by Udalski et al. (1999b), but the sample still contains a few rather faint variables that are probably P0 Cepheids. The clearly broken P-C and P-L relations, corrected as before for variable internal absorption, are shown in Fig. 2. They are adequately fit by two linear regressions with different slopes. The slopes, even for different positions of the break point, are so similar to the slopes of the two segments of the P0 Cepheids that it is assumed that corresponding segments are parallel. In that case, the P-C and P-L relations

yield a good compromise break at $\log P = 0.4$. The equations of the different relations are given in Table 2 following the scheme $x = a \log P + b$.

The relative position of the P-L relation of fundamental-mode and first-overtone Cepheids suggests a period ratio at constant luminosity of metal-poor Cepheids of P0/P1 = 1.4.

We use the occasion to also revise here the P-C and P-L relations of LMC. They were derived in Paper II (Sandage et al. 2004) from a sample of 634 Cepheids using *B*, *V*, and *I* photometry by Udalski et al. (1999a) and other sources. The relations showed a highly significant break at $\log P = 1.0$, but about 100 Cepheids with $\log P < 0.4$ were excluded. With the inclusion of these objects, the best-fit break point is shifted to $\log P = 0.9$. The corresponding P-L relations are given in Table 5 below.

3. IC 1613

The first 27 Cepheids in IC 1613 were found by W. Baade. He did not publish them because they defined a P-L relation

Table 2. P-C and P-L relations of first-overtone (P1) Cepheids in SMC.

	$\log P < 0.4$		$\log P > 0.4$	
$(B-V)^0$	0.191 ± 0.021	0.293 ± 0.003	0.415 ± 0.020	0.203 ± 0.007
$(V-I)^0$	0.166 ± 0.018	0.458 ± 0.003	0.311 ± 0.016	0.401 ± 0.007
M_B^0	-3.007 ± 0.076	-1.461 ± 0.013	-2.091 ± 0.071	-1.827 ± 0.030
M_V^0	-3.203 ± 0.060	-1.759 ± 0.010	-2.531 ± 0.056	-2.028 ± 0.026
M_I^0	-3.374 ± 0.046	-2.210 ± 0.008	-2.842 ± 0.043	-2.423 ± 0.020

much flatter than in LMC, which he suspected could be caused by a scale error in his photographic mpg magnitudes. Sandage (1971), after fitting the magnitudes into a photoelectric *B* scale, confirmed the flat slope, but showed that the deviations from the LMC slope could be explained by the intrinsic width of the instability strip and a statistical fluke. Freedman (1988a) determined *CCD* magnitudes in the UBV system for nine of Baade's Cepheids, but their number is too small to provide a reliable slope; she fitted them to the LMC P-L relations, but a flatter slope fits the data at least as well. Udalski et al. (2001) provided mean *VI* magnitudes for many Cepheids in IC 1613 and found no significant deviations from the LMC slope known at that time. Yet additional *BVI* photometry of the Cepheids in IC 1613 by Antonello et al. (2006) reopened the question of the agreement between IC 1613 and LMC, a question that gained new weight after the P-L and P-C relations of LMC were shown to display a pronounced break at $\log P = 1.0$ (Tammann & Reindl 2002; Tammann et al. 2002b; Sandage et al. 2004, Paper II; see also Kanbur & Ngeow 2004; Ngeow et al. 2005; Koen & Siluyele 2007; Kanbur et al. 2007). Additional Cepheids in IC 1613 were found by Bernard et al. (2010), which have short or very short periods and are useful for the definition of the tails of the P-L relations.

Several authors have obtained photometry of IC 1613 Cepheids in the near- or mid-infrared. These cannot, however, be compared with LMC or SMC, either because the number of Cepheids is too small or the corresponding data are missing in the Clouds.

The Cepheids of IC 1613 are here compared with those of *SMC*. This is because the two galaxies have very similar metallicities and as a consequence of this a significant population of very short-period Cepheids, in contrast to LMC.

3.1. The data

The following Cepheid data were used to define the P-L and P-C relations of IC 1613:

1. Udalski et al. (2001) obtained mean *V* and *I* photometry for 138 Cepheids in the framework of the extensive OGLE II project (78 with $\log P > 0.4$). They excluded the overtone pulsators, two type II Cepheids, two blends, and the outlyer 13 682 (=V39 from Sandage 1971). We exclude in addition the Cepheids with $\log P < 0.4$ because their separation into fundamental and overtone pulsators is ambiguous. This leaves 60 fundamental pulsators in the sample.

2. Antonello et al. (2006) published mean *BVRI* magnitudes of 49 P0 Cepheids from the sample of Udalski et al. (2001) and 3 additional ones. They observed them at only a few epochs, but used the known light curves in *V* and *I* to also construct the light curves in *B* and *R* following the method of Freedman (1988a). They provided mean *B* magnitudes for 49, *V* magnitudes for 52, and *I* magnitudes for

51 Cepheids. (The *R* magnitudes are not considered here.) Six of the 48 Cepheids with three-color photometry fall outside the boundary defined by SMC in the $(B-V)$ versus $(V-I)$ diagram (see Fig. 2a below); these objects are excluded.

3. Dolphin et al. (2001) added five P0 Cepheids with *V* and *I* photometry.

4. Bernard et al. (2010) presented ACS HST photometry of many faint variables in IC 1613 including 49 Cepheids. Twenty-six Cepheids, all with *VI* photometry, are identified by the authors as P0 pulsators, 12 of which are also in the sample of Udalski et al. (2001). Of the remaining 23 Cepheids, 16 are classified as first-overtone (P1) pulsators.

We tentatively added the 147-day Cepheid V22 with *BVI* photometry by Freedman (1988a); the photometry should be confirmed because other Cepheids from the same source agree poorly with Antonello et al. (2006).

The four samples were merged resulting in a sample of 124 P0 Cepheids, of which 22 were excluded as outliers (marked in Fig. 3) in addition to those already discussed. Mean magnitudes from more than one source were averaged, as also done for the following galaxies. The final sample consists of 102 P0 Cepheids with *V* and *I* photometry, of which 68 have also *B* magnitudes. The 16 P1 Cepheids have *B*, *V*, and *I* magnitudes.

3.2. The P-C and P-L relations of IC 1613

The P-C relations in $(B-V)^0$ and $(V-I)^0$ and the P-L relations in *B*, *V*, and *I* of the P0 Cepheids and the excluded variables are shown in the five panels of Fig. 1.

The P-C and P-L relations in panels a–e are described well by the broken P-C and P-L relations of SMC adopted in Sect. 2 (full lines). In the case of the P-L relations, SMC was shifted in apparent magnitude to achieve the best fit. The break at $\log P = 0.55$ is clearly visible in all five panels. The scatter in the data for the IC 1613 Cepheids about the SMC relations in the five panels is the same as of the SMC Cepheids themselves. Forced linear fits over the whole period range for the IC 1613 and SMC Cepheids agree to within 1σ. The relations of the two galaxies are indistinguishable.

3.3. Derived parameters of IC 1613: reddening and distance

The Cepheids with three-color photometry are plotted in a two-color diagram $(B-V)^0$ versus $(V-I)^0$ in Fig. 4a, where the region defined by SMC Cepheids is also shown. The majority of the IC 1613 Cepheids lie within the SMC boundaries except six, which are identified in the figure. These stars are possible P1 pulsators (cf. their position in Fig. 4e), but are excluded in the following discussion.
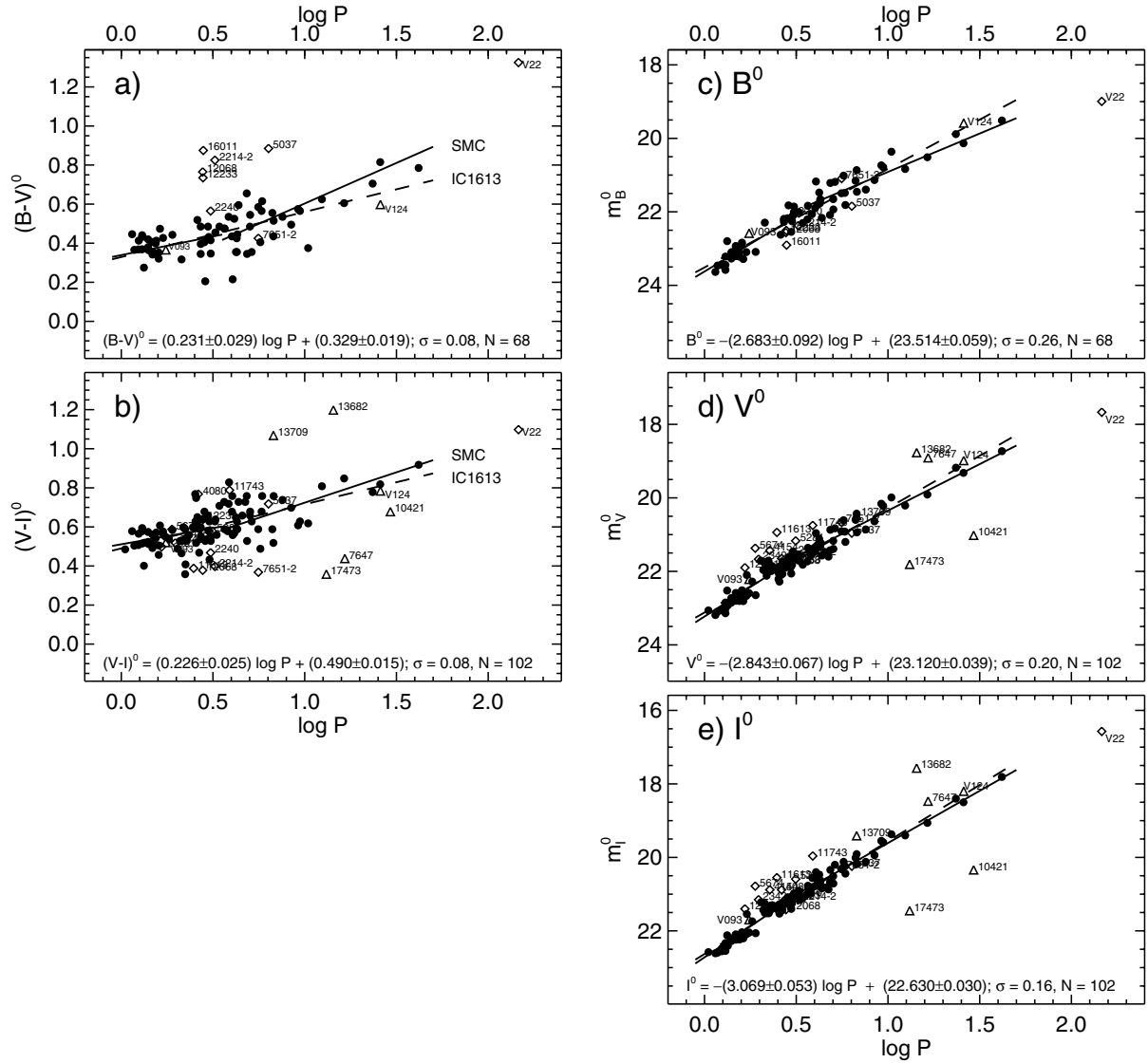
Fig. 3. The P-C and P-L relations of the fundamental-mode (P0) Cepheids of IC 1613. The full lines are the corresponding relations of SMC. Forced linear fits over the whole period interval are shown as dashed lines (their equations are given at the bottom of each panel). The agreement between IC 1613 and SMC is striking. Cepheids excluded by the original authors (triangles) or by ourselves (diamonds) are shown as open symbols.

A comparison of the colors $(B-V)^0$ and $(V-I)^0$ of the P0 and P1 Cepheids of IC 1613 with the P-C relation of SMC leads to their individual color excesses $E(B-V)$ and $E(V-I)$. The latter are transformed into $E(B-V)$ (we note that $E(V-I) = 1.28E(B-V)$). The mean values of $E(B-V)$s are adopted and plotted against period in Fig. 4b. The slight period dependence is neglected. The scatter in the individual excesses of $\sigma E(B-V) = 0.06$, which is smaller than in SMC (0.09), is due to the intrinsic color width of the instability strip. The overall mean internal excess of $E(B-V) = 0.003 \pm 0.010$ is negligible. The tacit assumption is that the intrinsic color of Cepheids in IC 1613 is the same as in SMC in agreement with their similar metallicities. If IC 1613 Cepheids were intrinsically bluer, their blueness would have to be closely compensated for by the corresponding amount of internal absorption, which seems far-fetched.

The P-L relations in B^0, V^0, and I^0 of the P0 and P1 Cepheids are shown in Figs. 4c to e. The IC 1613 data fit the SMC relations very well, their scatter being the same as for the SMC Cepheids proper. On the assumption that P0 and P1 Cepheids in IC 1613

and SMC have the same luminosity and that $(m - M)^0_{\rm SMC} = 18.93$, the individual distances of IC 1613 Cepheids are derived by comparing them with the corresponding P-L relations of SMC from Sect. 2. The resulting distances are plotted against period in Figs. 4f to h. A certain problem arises from the B data yielding distances that depend (mildly) on period. This general problem is addressed in Sect. 8. The mean distances, derived from each color, read at the median period, are shown in the corresponding panels of Fig. 4. If averaged over all three colors, the P0 and P1 Cepheids are found to correspond to $(m - M)^0 = 24.32 \pm 0.02$ and 24.38 ± 0.03, respectively. We adopt a number-weighted overall mean of 24.34 ± 0.03.

Cepheid distances of IC 1613 have been determined by different authors. A selection is compiled in Table 3 in chronological order. Distances that are based on assuming the LMC as their zero-point are normalized here to $(m - M)^0_{\rm LMC} = 18.52$ (TSR 08a, Table 6), those based on SMC are normalized to $(m - M)^0_{\rm SMC} = 18.93$. At first sight, the distances, even if based on the LMC, agree to within ± 0.1 mag. However, the agreement
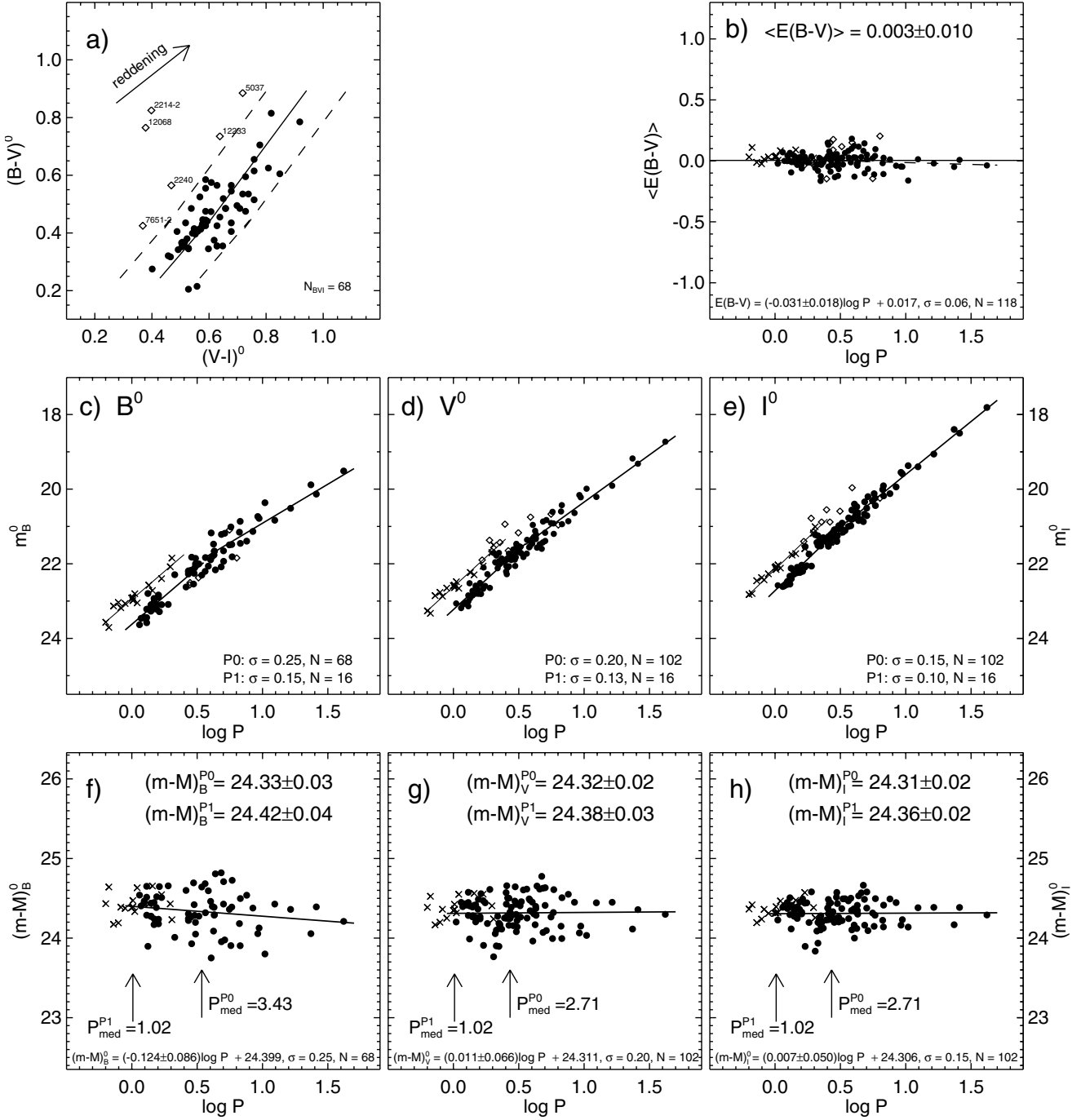
Fig. 4. a) The two-color index diagram $(B-V)^0$ versus $(V-I)^0$ of the P0 Cepheids of IC 1613. The region of SMC Cepheids is outlined. Cepheids outside this region are identified and shown as open diamonds. They are repeated in the following panels, but not used for the fits. **b)** The individual internal color excesses $E(B-V)$ and $E(V-I)$, combined here into mean values of $\langle E(B-V) \rangle$, as a function of $\log P$. **c)**–**e)** The cleaned P-L relations in B, V, and I of the P0 Cepheids (dots) and P1 (crosses) Cepheids. The full and thin lines are the SMC P-L relations for P0 and P1 pulsators, respectively, fitted to the data. **f)**–**h)** The individual true distance moduli of the Cepheids of IC 1613 as a function of $\log P$. The full lines are fits to only the P0 Cepheids; their equations are indicated at the bottom of the panels. The mean distances, read at the median period P_{med}, are shown for P0 and P1 Cepheids for each color.

of the $E(B-V)$ values in Col. 2 is poor in some cases. Total excesses of $E(B-V) > 0.06$ (i.e. 0.035 mag in excess of the Galactic contribution) imply that the IC 1613 Cepheids are significantly bluer in $(B-V)$ than even those in SMC, which invalidates the proposed use of the relatively red LMC Cepheids as a template.

Four entries in Table 3, designated with a (W) in Col. 4, have above average distances. They were determined by means of so-called Wesenheit magnitudes m_W, which are defined as $m_W(V) = m_V^{obs} - R_V(B-V)^{obs}$ or $m_W(I) = m_I^{obs} - R_I(V-I)^{obs}$, where R is the ratio of total to selective absorption. These pseudomagnitudes were originally introduced by van den Bergh (1968) and have

Table 3. Cepheid distances of IC 1613.

$(m-M)^0$	$E(B-V)$	Cal.	Passband	Source
(1)	(2)	(3)	(4)	(5)
24.55	0.03	Gal.	$m_{\rm pg}$	Sandage (1971)
24.11 ± 0.25	0.05	LMC	B	de Vaucouleurs (1978)
24.31 ± 0.11	0.03	Gal.	H	McAlary et al. (1984)
24.29 ± 0.11	–	LMC	$BVRIH$	Freedman (1988b)
24.41 ± 0.14	~0.04	LMC	$BV(W)$	″
24.44 ± 0.13	0.03	LMC	$BVRI$	Madore & Freedman (1991)
24.52 ± 0.10	(0.07)	LMC	$VI(W)$	Macri et al. (2001)
24.45 ± 0.07	0.025	LMC	$VI(W)$	Udalski et al. (2001)
24.44 ± 0.13	–	SMC	$VI(W)$	Dolphin et al. (2003)
24.31 ± 0.04	0.09	LMC	JK	Pietrzyński et al. (2006)
24.25 ± 0.20	0.07:	LMC	$BVRI$	Antonello et al. (2006)
24.48 ± 0.12	0.024	LMC	$BVRI$	″
24.32 ± 0.02	0.025	SMC	BVI	TSR 08a
24.29 ± 0.12	0.08	LMC	3.6; 4.5 μm	Freedman et al. (2009)
24.30 ± 0.07	–	LMC	3.6; 4.5 μm	Ngeow et al. (2009)
24.34 ± 0.03	0.025	SMC	BVI	Present paper

been widely used since to account for absorption in an approximate way. However, the method is only applicable to Cepheids with identical P-C relations, i.e. of the same metallicity. In the case of different *intrinsic* colors, not only the reddening but also the intrinsic color difference is multiplied with the value R, which leads to systematic distance errors.

4. WLM

Sandage & Carlson (1985a) found the first 15 Cepheids in WLM, all of which have periods shorter than $10^{\rm d}$, and provided their light curves in B. For five of them, Valcheva et al. (2007) determined J magnitudes. Pietrzyński et al. (2007) published the data of 59 Cepheids with V and I magnitudes, which include data for 14 of the Cepheids by Sandage & Carlson. Gieren et al. (2008) added J and K magnitudes for 31 of Pietrzyński's et al. Cepheids. No P1 Cepheids had previously been identified in WLM.

The P-C and P-L relations of the Cepheids by Pietrzyński et al., corrected for foreground reddening of $E(V-I) = 0.047$ (Schlegel et al. 1998), are exhibited in Figs. 5a to c where the corresponding relations of SMC are drawn as full lines. Three objects are excluded by the authors as being blends or overtone pulsators; one additional outlier (cep55) was excluded by us. Of the remaining 55 Cepheids, 45 are accepted as P0 Cepheids, the remainder very likely being P1 pulsators. With this interpretation, the match of WLM with SMC becomes impressively good. The scatter of the points about the SMC templets is almost the same as that of the SMC Cepheids.

The comparison of the $(V-I)$ colors of the P0 and P1 Cepheids with the adopted SMC P-C templets leads to the individual color excesses as a function of period (Fig. 5d). The regression (dashed line), whose equation is given at the bottom of the panel, is flat and suggests a slightly negative mean color excess (-0.027 ± 0.041 mag). We interpret this as zero internal absorption.

The 45 P0 magnitudes in V and I yield, if compared with the absolute magnitudes from the P-L relation of SMC, individual distances as a function of $\log P$ (Figs. 5e and f). The dependence of the distances on $\log P$ is insignificant. Their mean values, read at the median period, are indicated in the respective panels. The mean distance from the V and I magnitudes is $(m-M)^{\rm P0} = 24.93 \pm 0.03$.

Treating the ten P1 Cepheids in an analogous way gives mean distances in V and I as shown in panels e and f of Fig. 5 and, if combined, $(m-M)^{\rm P1} = 25.01 \pm 0.02$.

A number-weighted mean of the P0 distances and the somewhat larger P1 distances gives $(m-M)^0 = 24.95 \pm 0.03$ for WLM, which we adopt.

The distance modulus of $(m-M)^0 = 25.16$ (normalized to $(m-M)^0_{\rm LMC} = 18.52$) of Pietrzyński et al., derived from the same data, yet based on Wesenheit pseudo-magnitudes and using LMC as a templet, is 0.21 mag larger than found here. The modulus of $(m-M)^0 = 24.94 \pm 0.04$ of Gieren et al. (2008) is close to the present solution, but the proposed large reddening of $E(B-V) = 0.08$ mag, implying an *internal* reddening of $E(V-I) = 0.03$, would make the WLM Cepheids unusually blue. The modulus of 24.86 ± 0.14 from four Cepheids with J magnitudes (Valcheva et al. 2007) is in statistical agreement with the present value, which is perfectly matched by the value of 24.95 ± 0.10 from four Cepheids with 3.6 and 4.5 μm mag (Ngeow et al. 2009).

5. Pegasus = DDO 216

The first 6 Cepheids discovered in Pegasus, a peculiar dwarf system, were measured in R magnitudes by Hoessel et al. (1990) whose discussion led to a modulus of $(m-M)^0 = 26.22$, which is certainly too large. Meschin et al. (2009) determined V and I magnitudes for 18 P0 Cepheids as well as for 8 Cepheids that they identified as P1 pulsators. These two groups are compared in the following with the corresponding, calibrated templets of P-C and P-L relations provided by SMC in Sect. 2.

The P0 Cepheids of Meschin et al. (2009) are shown, after correction for the Galactic color excess of 0.066 (Schlegel et al. 1998), in the period-color plane of Fig. 6a, where the P-C relation of SMC is overplotted. The rather red Cepheids appear to follow a shallow P-C relation, but the scatter in their data is very large (0.20 mag). The mean color excess derived from Fig. 6d of $E(V-I) = 0.103 \pm 0.085$, formally decreasing with period, is very poorly determined. We interpret this as zero absorption for the moment, but return to this point below.

The P-L relations in V and I of the P0 and P1 Cepheids are shown in Figs. 6b and c together with the fitted SMC templets. Eye inspection shows the fits to be excellent. The scatter in V of the Pegasus Cepheids about the SMC line is essentially the same as for the SMC Cepheids. The scatter in I is here larger than in SMC, suggesting that mainly the I magnitudes cause the large scatter in $(V-I)$. Hence, the latter may be affected by observational errors.

A comparison of the individual P0 Cepheids with the calibrated SMC P-L relations leads to the individual distance moduli plotted versus $\log P$ in Figs. 6e and f. Allowing for their mild increase with $\log P$ – the notorious effect is discussed further in Sect. 8 – we read the mean moduli in V and I at the median period. The mean distances in V and I, as shown in the respective panels of Fig. 6, give a combined distance of $(m-M)^{\rm P0} = 24.86 \pm 0.06$.

The eight P1 Cepheids, analyzed using the corresponding templet P-L relations of SMC, lead to the mean moduli in V and I as shown in Figs. 6e and f and to a combined modulus of $(m-M)^{\rm P1} = 24.88 \pm 0.06$ in good agreement with the P0 Cepheids.

Yet the above assumption of zero internal absorption needs comment. The galaxy has a highly variable background, six Cepheids lying on heavy background and seven are far outlying, but the individual distances show no correlation with
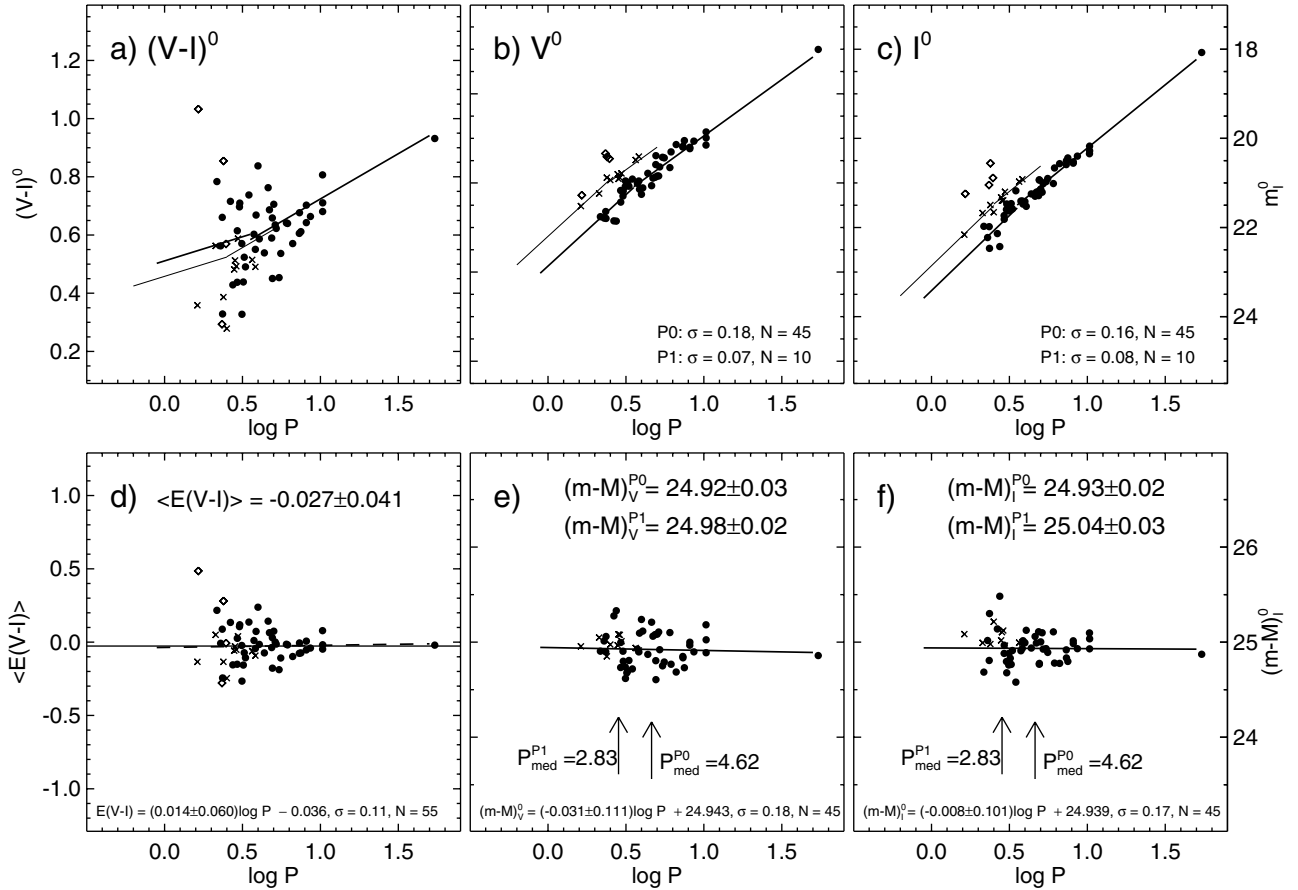
Fig. 5. **a)** The P-C relation in $(V-I)$ of WLM. Full dots are P0 Cepheids throughout, crosses P1 Cepheids, and open diamonds excluded variables. The thick line is the P-C relation of SMC for P0, the thin line for P1 Cepheids. **b)**, **c)** The P-L relations in V and I of the same objects as in **a)**. The full lines are the P-L relations of the P0 (thick line) and P1 (thin line) Cepheids in SMC, shifted in magnitude to fit the WLM data. The similarity of the WLM and SMC Cepheids is apparent. **d)** The internal color excesses $E(V-I)$ of the P0 and P1 Cepheids in WLM as a function of $\log P$ inferred from a comparison with the adopted SMC templets. – **e)**, **f)** The individual true distance moduli of the P0 and P1 Cepheids as a function of $\log P$ inferred from a comparison of the true apparent V and I magnitudes with the corresponding SMC templets. The full line is a fit to only the P0 Cepheids; their equations are indicated at the bottom of the panels. The mean distances are read at the indicated median period $P_{\rm med}$.

position. This argues against internal absorption. In addition, the large scatter in the P-L relation for I cannot be explained by absorption because in this case the scatter in V would be even larger. The assumption of negligible internal absorption therefore seems to be justified.

The overall mean distance, including P0 and P1 Cepheids and V and I colors, is $(m-M)^0 = 24.87 \pm 0.06$, which we adopt.

Meschin et al. (2009) compared only the V magnitudes of 11 longer-period P0 Cepheids with the LMC P-L relations in V of Paper II and Fouqué et al. (2007). This has led to a somewhat large modulus of $(m-M)^0 = 25.13 \pm 0.11$.

6. Sextans A and B

The two Im dwarf galaxies Sextans A and Sextans B lie at the same TRGB distance (Tammann et al. 2008b, hereafter TSR 08b) and are separated in projection by only $\sim$200 kpc. Their recession velocities agree to within $25 \, \rm km \, s^{-1}$, and they have about the same luminosity and equal, extremely low metallicities (Sakai et al. 2004). They form a pair, hence their Cepheid populations are merged here.

The first Cepheids in Sextans A & B were discussed by Sandage & Carlson (1982, 1985a). Piotto et al. (1994) found

some additional ones and gave mean BVI magnitudes for a total of 17 Cepheids (10 in Sextans A and 7 in Sextans B; 4 Cepheids have only B magnitudes). The variables P10, P15, and P25 in Sextans A and P17 in Sextans B are probably O1 pulsators. Dolphin et al. (2003) complemented the sample in Sextans A with 82 short-period Cepheids with V and I magnitudes, of which 39 are identified by the authors as P0 pulsators. In an earlier discussion, we treated the P1 pulsators as P0 Cepheids and concluded that the P-L relations of Sextans A & B are much flatter than those of SMC (Sandage & Tammann 2008); an interpretation that cannot be maintained in the light of the new data.

The colors $(B-V)^0$ and $(V-I)^0$ of the P0 Cepheids are shown as dots (Sextans A) and open triangles (Sextans B) in Figs. 7a and b. Crosses represent P1 Cepheids. The P-C relations are very poorly determined because of the large scatter. Yet a comparison of the individual colors with the P-C relation of SMC leads to $E(B-V)$ and $E(V-I)$ excesses. The latter are converted to $E(B-V)$ and then averaged. The result is shown in Fig. 7c. The mean excesses depend little on period and give an overall mean consistent with $E(B-V) = 0.00$.

The B^0, V^0, and I^0 magnitudes of the P0 Cepheids in Sextans A (dots) and Sextans B (open triangles) as well as the P1 Cepheids of Sextans A (crosses) are plotted versus $\log P$ in
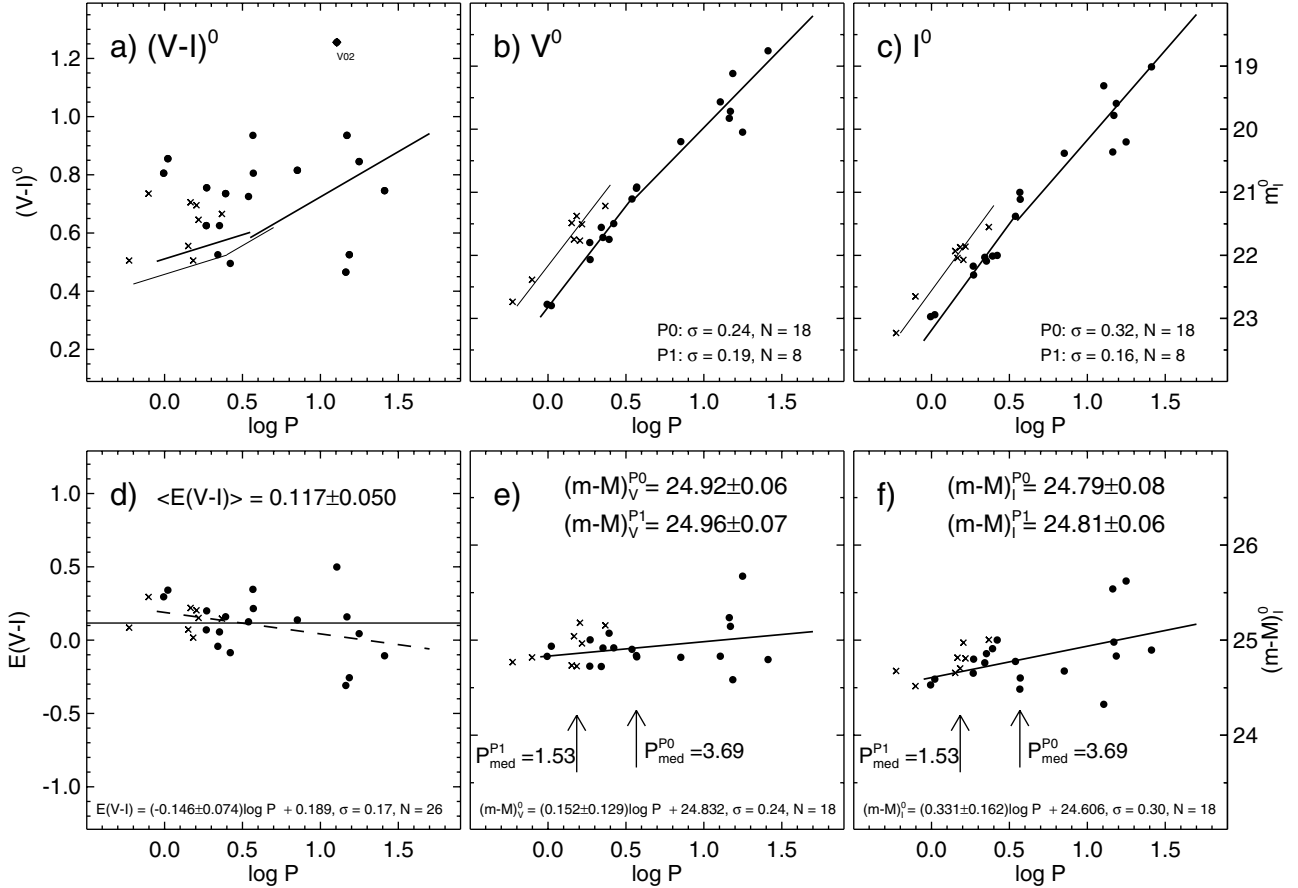
Fig. 6. Same as Fig. 5, but for the Cepheids in the Pegasus dwarf galaxy.

Figs. 7d to f. Of the seven Cepheids of Sextans B, six are taken as P0 pulsators, the seventh Cepheid may be a P1 pulsator and is omitted. The templet P-L relations of SMC (from Sect. 2) are shown as heavy lines. They are shifted in magnitude to provide an optimal fit to the data. The fit is as good as can be expected. The scatter about the templet lines is about the same as that of the SMC Cepheids.

The B^0, V^0, and I^0 magnitudes of the P0 Cepheids are compared with the P-L relations of SMC (Sect. 2). This leads to their individual distances as plotted versus log P in Figs. 7g to i. The distances depend slightly on period, but the effect is barely significant; we assume, as before, the mean distance moduli read at the median period of the Cepheids as a reasonable compromise. The mean distances in V and I agree well. The mean modulus in B is significantly lower, but is based on only 13 Cepheids. The number-weighted mean over the three colors is $(m - M)^{P0} = 25.60 \pm 0.05$.

The 43 P1 Cepheids with V^0 and I^0 magnitudes from Dolphin et al. (2003) are compared with the appropriate P-L relations of SMC, shown as thin lines. The resulting individual distances are plotted versus $\log P$ in Figs. 7h and i (crosses). They yield a mean modulus of $(m - M)^{P1} = 25.59 \pm 0.03$ in agreement with the P0 data. We adopt for the common distance modulus of Sextans A & B $(m - M)^0_{\mathrm{Sex}} = 25.60 \pm 0.03$, which is the mean of the distances of the P0 and P1 pulsators. – If Sextans A and Sextans B are treated separately, one finds an overall modulus of $(m - M)^0 = 25.63 \pm 0.03$ for Sextans A and $(m - M)^0 = 25.53 \pm 0.10$ for Sextans B. The statistical agreement

of these two numbers justifies the combination of the two galaxies into one data set.

Previous results for the true Cepheid modulus of Sextans A are 25.71 ± 0.20 (Piotto et al. 1994, including Sextans B) and $\sim 25.87 \pm 0.15$ (Sakai et al. 1996). The value of 25.66 ± 0.03 of Dolphin et al. (2003) is based on the zero-point of SMC, adjusted here to $(m - M)^0_{\mathrm{SMC}} = 18.93$. The authors converted their V and I magnitudes into Wesenheit magnitudes, which in this case is not objectionable provided that the low-metallicity Cepheids in Sextans A and SMC indeed have identical colors.

If the present interpretation is taken at face value, that the P-C and P-L relations of Sextans A & B are at least similar to the ones of SMC, it follows that below a certain limit of $[\mathrm{O/H}]_{T_e} \sim 8.0$ the form and the zero-point of these relations become quite insensitive to metallicity changes of a factor of ~ 3.

7. Leo A

Dolphin et al. (2002) determined the mean V and R magnitudes for the first 66 unambiguous classical Cepheids in Leo A, of which the authors classified 19 as P0 and 38 as P1 pulsators. The P0 Cepheids have periods of between 0.86 and 2.13 days, and the P1 Cepheids of between 0.46 and 1.22 days. These are the shortest-period Cepheids known. Dolphin et al. (2002) explain their high frequency – as Sandage & Carlson (1985b) did before in the case of WLM – by the metal-dependent size of the evolutionary loops that feed the instability strip (see Hofmeister 1967; Becker et al. 1977). The absence of Cepheids with longer
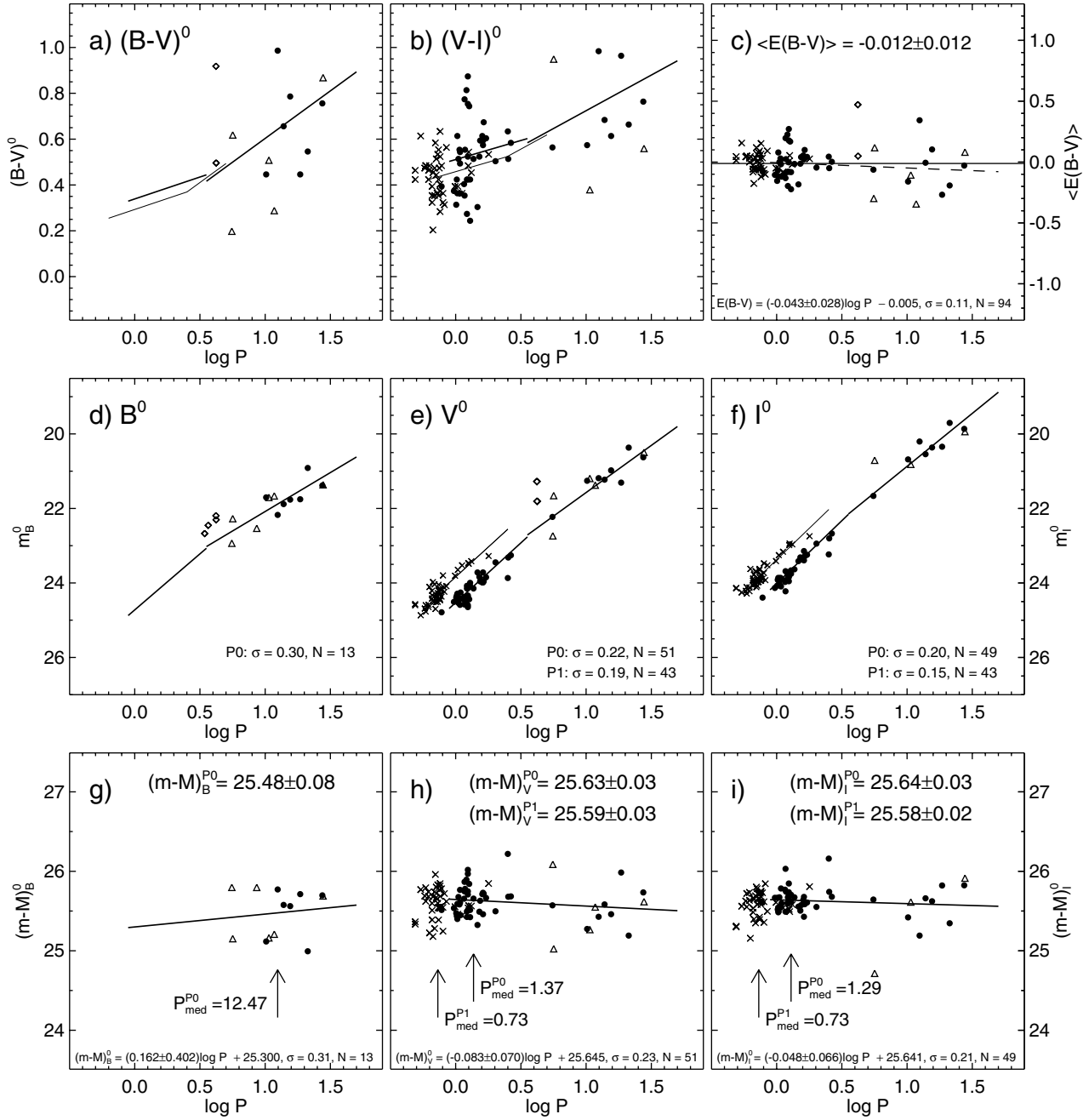
Fig. 7. Analogous to Fig. 4 but for Cepheids in Sextans A & B and augmented here with B and $(B-V)$ data.

periods is the result of the specific star formation rate and the small sample size according to Dolphin et al. (2002).

The P-L relations in V, corrected for Galactic absorption, of the P0 (dots) and P1 (crosses) Cepheids are shown in Fig. 8a. The data can be described well by shifting the templet relations of SMC in apparent magnitude. We note that the P0 templet is defined down to only ~1 day and the P1 templet down to 0.6 days. The P-L relations in R are not helpful because the corresponding data for SMC are unavailable. It must therefore be assumed that the internal absorption is negligible, which seems plausible in the light of the preceding dwarf galaxies.

The individual distances of the P0 and P1 Cepheids follow directly from a comparison of their V^0 magnitudes with

the corresponding calibrated P-L relations of SMC. The dependence of the resulting distances on $\log P$ is insignificant as seen in Figs. 8b and c. The mean distance modulus, read at median period, is $(m - M)^{P0} = 24.67 \pm 0.05$ and $(m - M)^{P1} = 24.55 \pm 0.02$. We adopt the number-weighted mean of $(m-M)^0 = 24.59 \pm 0.03$.

Dolphin et al. (2003, Table 3) found for P0 and P1 Cepheids $(m - M)^0 = 24.66$ and 24.54, respectively (adjusted to $(m - M)_{\rm SMC} = 18.93$) in excellent agreement with the present result.

8. Discussion of distances

The basic assumption of using Cepheids as distance indicators is that they have the same color (for the determination of the
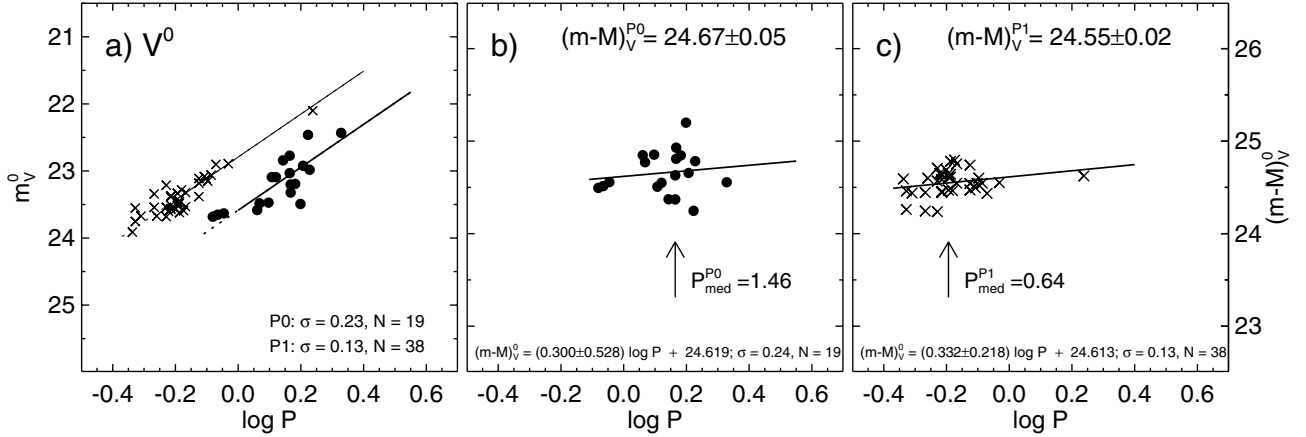
Fig. 8. **a)** The P-L relation in V of the P0 (dots) and P1 (crosses) Cepheids in Leo A. The corresponding, magnitude-shifted relations of SMC are shown as heavy lines for P0's and thin lines for P1's. **b)**, **c)** The individual distances of the P0 and P1 Cepheids plotted versus $\log P$.

Table 4. Comparison of Cepheid distances with RR Lyr and TRGB distances.

	SMC	IC 1613	WLM	Pegasus	Sextans A & B	Leo A
Cep P0	18.93[1]	24.32 ± 0.02	24.93 ± 0.03	24.86 ± 0.06	25.60 ± 0.05	24.67 ± 0.05
Cep P1	18.93[1)]	24.38 ± 0.03	25.01 ± 0.02	24.88 ± 0.06	25.59 ± 0.03	24.55 ± 0.02
Cep adopted	**18.93[1]**	**24.34 ± 0.03**	**24.95 ± 0.03**	**24.87 ± 0.06**	**25.60 ± 0.04**	**24.59 ± 0.03**
RR Lyr	18.98	24.35	$\cdots$	$\cdots$	$\cdots$	24.54
TRGB	19.00	24.32	24.90	24.84	25.72	24.57
$\Delta(m-M)^0$	$\cdots$	0.02	0.05	0.03	-0.12	0.02

Notes. [(1)] Used as calibrator (see Paper III).

reddening) and luminosity at a given period. The minimum conditions for this are that they pulsate in the same mode and that their metallicity is equal. Whether additional conditions (such as equal He content) should be fulfilled remains an open question.

For every metallicity, one ideally requires a corresponding templet galaxy with well defined P-C and P-L relations and an independently known distance. At present, only the Galaxy, LMC, and SMC fulfill these conditions to serve as templets. Their remaining distance errors of $0.05-0.10$ add to the systematic distance error of other galaxies.

The original goal of the present paper was to compare the P0 Cepheids of IC 1613 with those of the SMC because the two galaxies have, within the errors, the same metallicity. The same holds for the Cepheids of the Pegasus dwarf galaxy, which were therefore included. On the basis of the equal metallicities, it is expected that the three sets of Cepheids define very similar P-C and P-L relations. As shown above, the expectation is fully confirmed. The next step was to also include the Cepheids in WLM, the galaxy pair Sextans A & B, and Leo A, although they are more metal-deficient than SMC by factors of 1.7, 3, and 4, respectively. In spite of this, no significant differences were found between their P-C and P-L relations and those of SMC. This suggests that for very low metallicities ([O/H]$_{T_e} \lesssim 8.0$) even substantial variations in the metallicity have only mild, if any, effects on the P-C and P-L relations. This is surprising in as much as the metallicity *increase* of a factor of 2.3 from SMC to LMC causes striking differences between the P-C and P-L relations, e.g. the overluminosity of the LMC Cepheids, their relative paucity below $\log P = 0.4$, and the break of the LMC

relations at $\log P = 0.9$ instead of 0.55 in SMC (see Fig. 10 below).

The near equality of the properties of the Cepheids in the present sample suggests that the errors of the adopted distances in Table 4 are caused mainly by statistics and the zero-point error of the SMC.

Yet the slopes of the P-C and P-L relations of two galaxies are hardly ever identical – be it for intrinsic or statistical reasons. Any slope difference of the P-C relations of the galaxy under investigation and the galaxy used as a templet will lead to color excesses that vary with period. This is not a serious problem in the present case because all excesses are vanishingly small.

In addition, any slope differences between the P-L relation of the galaxy under investigation and the templet P-L relation will cause the distances of individual Cepheids to depend on period. If the former has the slope $p_1 \pm \epsilon_1$ and the latter an observed slope of $p_2 \pm \epsilon_2$, then the slope of the $(m-M) - \log P$ relation will have the slope $\pi = p_1 - p_2$ with a seemingly small error of $\pm \epsilon_2$ because the templet is assumed to be error-free. In principle, the problem cannot be solved because the slope differences may be real. Nevertheless, if we assume that the majority of the sample Cepheids follow the templet P-L relation, the best mean distance is read at their median period. This is justified, however, only if the templet P-L relation is well defined at this period, which is the case for the present sample of galaxies. The problem is aggravated whenever the centers of weight of the test and templet Cepheids lie at different periods, as happens frequently for more distant galaxies that are biased toward longer-period Cepheids. All published Cepheid distances we tested exhibit the
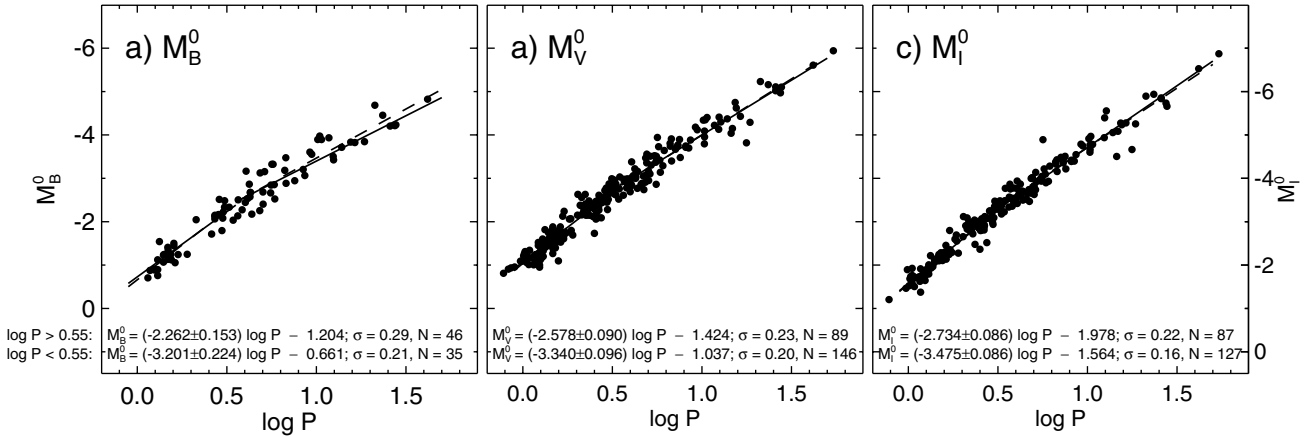
Fig. 9. Composite P-L relations in M_B, M_V, and M_I of the P0 Cepheids in IC 1613, WLM, Sextans A & B, the Pegasus dwarf, and Leo A using their adopted distances. The dashed lines are regressions to the Cepheids with $\log P \gtrsim 0.55$; their equations are given at the *bottom of each panel*. The full lines are the corresponding P-L relations of SMC. The two lines in each panel are almost congruent.

dependence of the modulus on $\log P$ (see e.g. Saha et al. 2006), which adds to the external error in the Cepheid distances more than is generally acknowledged.

In view of the possible remaining systematic errors, it is important to test the derived Cepheid distances in the light of *independent* distance determinations. The most reliable alternative distance indicators are RR Lyr stars and the tip of the red-giant branch (TRGB). The available data are compiled in Table 4. The P0, P1, and adopted Cepheid distances and their estimated internal errors are repeated from Sects. 3–7. The RR Lyr distances are taken from TSR 08a. The TRGB distances were compiled by TSR 08b and augmented here by some additional sources (Lee et al. 1993; Aparicio 1994; Minniti, & Zijlstra 1997; Méndez et al. 2002; Dolphin et al. 2003; Tully et al. 2006; Meschin et al. 2009; Dalcanton et al. 2009). In total, 22 measurements of the TRGB were used for the five galaxies in Table 4. They are homogenized to a common zero-point of $M^0_{\rm TRGB} = -4.05$ as determined from 19 RR Lyr distances (TSR 08a) and independently confirmed by Rizzi et al. (2007). Although theory predicts that the TRGB depends somewhat on metallicity, the sign of the correction remains under discussion.

The comparison in Table 4 is surprisingly good. P0 and P1 distances agree on average to within 0.01 ± 0.04 mag. The two RR Lyr distances deviate from the corresponding Cepheid distances by only ± 0.01. The mean difference between the Cepheid and TRGB distances is $\langle \Delta(m - M) \rangle = 0.00 \pm 0.03$. The null result not only supports the adopted zero-point distance of SMC, but provides a consistency check of the Population I and Population II distance scales. The rms of the distance differences is $\sigma_{(m-M)} = 0.07$ mag. Even if one allows a value as low as 0.05 for the random error in the TRGB distances, the random external error in the Cepheid distances is not more than 0.05 mag.

9. Results and conclusions

The P0 Cepheids in IC 1613, WLM, Pegasus, Sextans A & B, and Leo A (excluding SMC) are combined into composite P-L relations in B, V, and I, adopting the respective Cepheid distances derived in Sects. 3–7 (Fig. 9). The resulting P-L relations, whose equations are at the foot of Fig. 9, are indistinguishable from those for SMC. Over the period interval of $0.2 < \log P < 1.2$, the P-L relations of SMC and the five sample galaxies agree to better than 0.02 mag in V and I. In B, with

fewer variables the agreement is not quite as good. In addition, the P1 Cepheids define closely agreeing P-L relations for SMC and the combined sample of five galaxies. This proves – in agreement with our prediction – that the P-L relations of SMC hold for the equally metal-poor galaxies IC 1613, WLM, and Pegasus and even for the still more metal-poor Sextans A & B and probably also for Leo A. (In the case of Leo A, the comparison is restricted to Cepheids with $\log P < 0.4$.) The low-metallicity galaxies are therefore part of a family with (nearly) equal P-L relations. This holds of course also for the P-C relations, which are nothing else but the difference of the respective P-L relations.

Cepheids of higher metallicity, such as those in LMC and the Galactic Cepheids in the solar neighborhood, have distinctly different P-L and P-C relations. For convenience, the coefficients of the relevant equations for the P0 Cepheids are compiled here in Table 5 following the scheme $x = a \log P + b$. The equations for SMC and LMC follow from Sect. 2. The Galactic equations come from Paper I and the revision in Paper II.

The steep slopes of the Galactic P-L relations from Papers I and II corresponds to data for Cepheids in Galactic clusters and OB associations (Feast 1999) as well as Baade-Wesselink-Becker distances by Fouqué et al. (2003) and Barnes et al. (2003), the two fully independent methods leading to the same result. Criticism of the result was discussed by TSR 08b. The P-L relations of metal-rich Cepheids will be discussed in more detail in a forthcoming paper; it is possible that they experience a break at long periods ($\log P \gtrsim 1.6$), but this is irrelevant here.

The observed P-L relations of LMC are closely matched – including the break at $\sim 10^d$ – by theoretical P-L relations based on pulsation models (Marconi et al. 2005). The same models do not show a break at higher metallicities in agreement with the Galactic P-L relations adopted here.

Marconi et al. (2010) also derived theoretical P-L relations for ultra-low metallicities. They have no break and are somewhat flatter than in SMC up to $\log P = 0.55$, but are much steeper beyond that point. The comparison may not be justified because the adopted metallicity ($[O/H] \sim 7.0$) is lower than in SMC and even Leo A.

To illustrate the difference between the Cepheids in SMC, LMC, and the solar neighborhood, the P-C and P-L relations of SMC and LMC are plotted *relative* to those of the Galaxy in Fig. 10. In each panel, the Galactic relations are taken as

Table 5. Coefficients of the relevant P-C and P-L relations for P0 Cepheids.

| | SMC[1] [O/H] = 7.98 | | | | LMC[2] [O/H] = 8.36 | | | | Galaxy [O/H] = 8.62 | |
| | $\log P < 0.55$ | | $\log P > 0.55$ | | $\log P < 0.9$ | | $\log P > 0.9$ | | | |
	a	b	a	b	a	b	a	b	a	b
$(B-V)^0$	0.191 ±0.021	0.339 ±0.005	0.415 ±0.020	0.188 ±0.018	0.306 ±0.020	0.330 ±0.012	0.435 ±0.029	0.199 ±0.036	0.366 ±0.015	0.361 ±0.013
$(V-I)^0$	0.166 ±0.018	0.511 ±0.005	0.311 ±0.016	0.413 ±0.014	0.201 ±0.017	0.474 ±0.010	0.345 ±0.024	0.331 ±0.030	0.256 ±0.017	0.497 ±0.016
M_B^0	−3.007 ±0.076	−0.728 ±0.022	−2.091 ±0.071	−1.306 ±0.063	−2.491 ±0.067	−1.083 ±0.040	−2.021 ±0.100	−1.576 ±0.123	−2.692 ±0.093	−0.575 ±0.107
M_V^0	−3.203 ±0.060	−1.071 ±0.018	−2.531 ±0.056	−1.466 ±0.050	−2.787 ±0.048	−1.414 ±0.029	−2.505 ±0.074	−1.713 ±0.091	−3.087 ±0.085	−0.914 ±0.098
M_I^0	−3.374 ±0.046	−1.577 ±0.013	−2.842 ±0.043	−1.872 ±0.038	−3.008 ±0.032	−1.880 ±0.019	−2.812 ±0.057	−2.076 ±0.069	−3.348 ±0.083	−1.429 ±0.097

Notes. Slope coefficients that agree to within 1σ are underlined. [1] Adopted at $(m-M)^0_{\text{SMC}}$ = 18.93 (TSR 08b, Table 6); [2] adopted at $(m-M)^0_{\text{LMC}}$ = 18.52 (TSR 08b, Table 7).
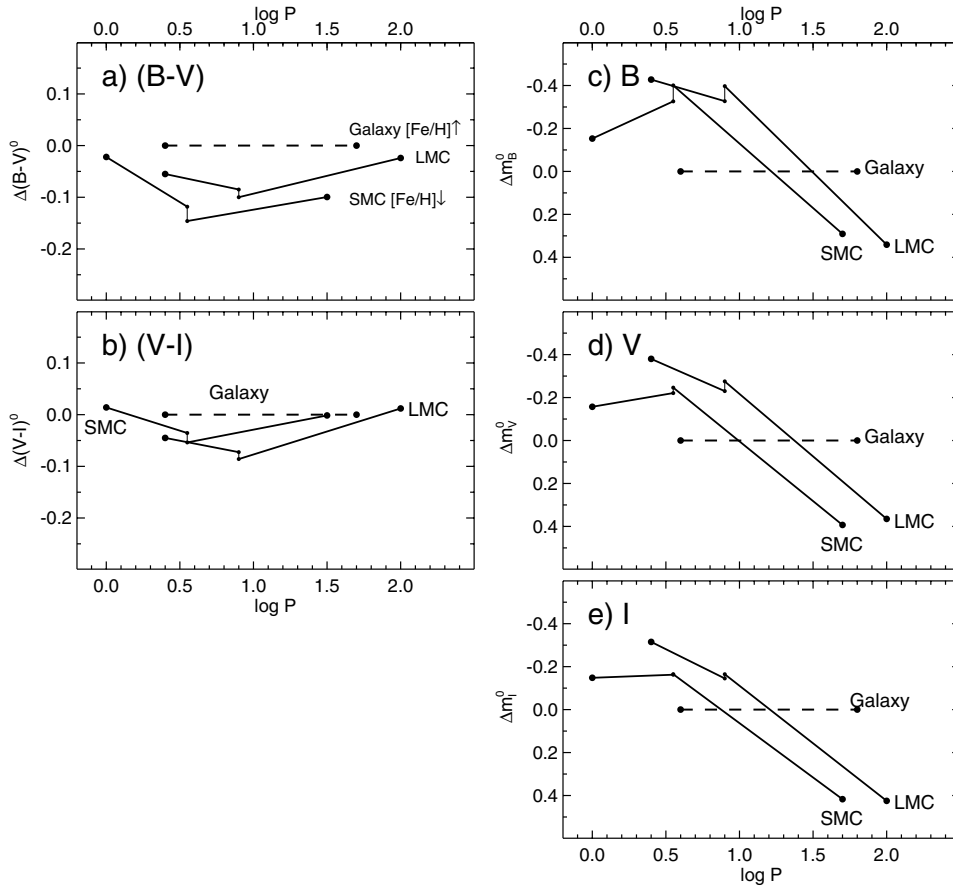

Fig. 10. a) The P-C relation in $(B-V)$ of P0 Cepheids in both the very metal-poor SMC and the relatively metal-poor LMC *relative* to the metal-rich Solar neighborhood. **b)** Same as a) but for $(V-I)$. **c)**–**e)** The P-L relations in B, V, and I, respectively, of the P0 Cepheids in SMC and LMC *relative* to the Solar neighborhood. The artificial spikes of the relations are due to statistical errors of the fits below and above the break. The lines are only drawn over the period range where they are well defined by observations.

reference and the *differences* in color and absolute magnitude of the Cepheids in the other two galaxies are shown as a function of $\log P$ (in the sense $x_{\text{LMC/SMC}} - x_{\text{Galaxy}}$).

As seen in Fig. 10a the LMC Cepheids are bluer in $(B-V)$ than their Galactic counterparts by up to 0.09 mag at $\log P$ = 0.9. The color difference is even larger between SMC and the

Galaxy, i.e. 0.13 mag at $\log P$ = 0.55. The red color of the Galactic Cepheids is due to their lower temperature and the blanketing effect of the metal lines (see Paper II).

The color differences in $(V-I)$ between the three galaxies in Fig. 10b are smaller. The LMC Cepheids are bluer than in the Galaxy by up to 0.08 mag. Unexpectedly, the SMC Cepheids are

redder than in LMC, yet still bluer than those in the Galaxy by a marginal amount of 0.04 mag or less, depending on period.

The P-L relations in B, V, and I of LMC and SMC are plotted relative to the Galactic P-L relations in Figs. 10c–e. The relations of LMC and SMC have similar characteristics and differ mainly in the zero-point, but they are both much flatter than in the Galaxy beyond the break point. At $\log P = 0.6$, LMC and SMC Cepheids are respectively brighter by 0.39 mag and 0.37 mag than in the Galaxy, whereas at $\log P = 1.7$ they are fainter by 0.14 and 0.29 mag, respectively. LMC Cepheids are brighter than in SMC by $0.15-0.20$ mag, somewhat depending on period. The significant luminosity differences of the Cepheids in the three galaxies cannot be explained by errors in the adopted distances, which are on the order of 0.1 mag. In addition, it is impossible to explain the different slopes of the P-L relations by distance errors.

We note that some of the *slopes* of the P-L relations in Table 5 show striking agreement. The slopes of SMC and LMC are essentially identical in B, V, and I above the break points, and the short-period SMC P-L relation in I has the same slope as Galactic Cepheids. In addition, the slopes of the P-C relations of SMC and LMC are the same to within $\sim 1\sigma$ for $\log P > 0.9$.

The Cepheids designated here as low-metallicity objects comprise in fact a wide metallicity range of $8.0 > [O/H]T_e > 7.4$. Their very similar P-L relations imply that they are quite insensitive at these low levels to metallicity changes. This is in sharp contrast to more metal-rich Cepheids where a change of only $\Delta[O/H]T_e = 0.26$ causes the pronounced differences between the LMC and Galactic P-L relations.

The use of Cepheids as distance indicators has been extended here to include fundamental-mode (P0) and first-overtone (P1) Cepheids with the shortest periods known. Among the known Cepheid population of the SMC, 47% of the P0 pulsators have periods less than $\log P = 0.4$, extending down to $\log P = 0.0$, and 37% are P1 pulsators with periods down to $\log P = -0.2$. The large number of these additional Cepheids makes them indispensable for accurate distance determinations. The distances derived here agree with independent RR Lyr and TRGB distances to within a few 0.01 mag.

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