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Variable stars in nearby galaxies*,**

VII. P-L relation in the *BVRI* bands of Cepheids in IC 1613

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ABSTRACT

A set of six *BVRI* observations collected with the WFI at the ESO 2.2 m telescope have been used to derive multicolor data of Cepheids in IC 1613 identified in previous surveys. Since part of the previously known data were obtained only in *VI* filters or without filter (*Wh*) bands, the method of Freedman has been applied to get reliable mean intensity values of Cepheid magnitudes in the various bands. The resulting slopes of the relations in the *BVI* bands are similar, within the uncertainties, to those previously obtained by other authors for the LMC. The distribution of the Cepheids in the period–color diagrams is compatible with a change near $P \sim 10$ d as observed in LMC. The distribution in the color–color diagrams is more similar to that in SMC, and this should be related to the very low metallicity of the galaxy.

Key words. stars: variables: Cepheids – galaxies: individual: IC 1613 – galaxies: Local Group – galaxies: stellar content

1. Introduction

In the framework of a project dedicated to the detection of variable stars in galaxies of the Local Group and to the accurate study of Cepheid light curve shape, we have obtained complementary photometric *BVRI* data for Cepheids in IC 1613 with the purpose of discussing the period–luminosity (P-L) relation. Cepheids are primary distance indicators and an extensive literature exists on their observed and theoretical properties, the P-L relation and the application to cosmological distance calibrations. Given the importance of such distance indicators, it is essential to fully understand the effects of variables such as metallicity and age, and to correct carefully for reddening effects. Multiwavelength data can be helpful in this context.

IC 1613 is a Local Group dwarf irregular galaxy with a low metallicity between –1.3 and –0.7 dex of its young population (Skillman et al. 2003). The results of a survey for variable stars in this galaxy obtained by Baade between 1929 and 1937 were later published by Sandage (1971). The resulting Cepheid P-L relation was rediscussed by Freedman (1988), and data on additional Cepheids were furtherly reported by Carlson & Sandage (1990). In 1995 we started a project dedicated to the CCD photometric survey for variability in this galaxy, by using a small telescope, the Dutch 0.9 m at ESO-La Silla. The purpose was to obtain good light curves of Cepheids and to compare their shape with that of Cepheids in different galaxies of different metallicities, and with nonlinear pulsation model predictions. Owing to the smallness of the telescope and the need of a good S/N ratio, the photometric observations were performed with no filter, i.e. in white light *Wh*-band. The results of the survey were reported in the first papers of the present series, along with a discussion of the advantages and shortcomings of the technique (Antonello et al. 1999a, Paper I; Antonello et al. 2000, Paper III; Mantegazza et al. 2001, Paper IV). The survey made by the OGLE group (Udalski et al. 2001) during 2000 in *V* and *I* bands allowed the authors to verify the possible effects of the different metallicity on the P-L relation in different galaxies. On the other hand, it was interesting to compare OGLE photometry results with ours (Antonello et al. 2002, Paper VI) in terms of the limiting magnitude.

Freedman (1988) showed how to exploit nonstandard photometry (e.g. photographic) light curves and just few standard photometry data to get reliable mean values of Cepheid standard magnitudes. We noted the possible utility of the method for studying Cepheids in external galaxies. The time consuming observational surveys for variability can be performed with (relatively) small telescopes and no filter, and just few accurate standard photometry CCD observations with larger telescopes are needed. In the present paper we demonstrate furtherly the

* Based on observations collected at ESO-La Silla; programs 66.D-0075A, 67.D-0013A, 68.D-0056A.
** Full Table 2 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/445/901

capability of the method in the case of IC 1613, and discuss the resulting P-L relation in the *BVRI* bands.

2. Observations

All of the observations with the WFI at the 2.2 m telescope of ESO-La Silla were performed in service mode. The WFI covers a field of view of 34×33 sq. arcmin and it includes eight CCD $2\text{k} \times 4\text{k}$ detectors, with a pixel size of 15 μm corresponding to 0.24 arcsec. The typical readout noise is 4.5 e^-/pixel and gain 2 e^-/ADU. The adopted *BVRI* filters were the No. 842, 843, 844 and 845.

BVRI data were collected during four nights in 2000. The single exposure times were 800 s (*B*), 300 s (*V*), 300 s (*R*) and 800 s (*I*). Another *BV* and a *BVR* data sets were obtained during two nights in 2001, and in that case the exposure times were 950 s (*B*), 550 s (*V*) and 425 s (*R*). The total times were the sum of two single exposures in the *BVR* bands, and of four single exposures in the *I* band. Standard star observations for the transformation to the standard system were performed during five nights. Usually, twenty bias images were combined, while a sufficient number of images of the sky or dome were combined for a good flat field correction in the four bands. The log of observations is reported in Table 1. The seeing ranged from $0\farcs8$ in the *R*-band for the best night to $1\farcs9$ in the *B*-band for the worst night.

The center, $\alpha = 1^{\rm h}04^{\rm m}50^{\rm s}$ (2000), $\delta = +2°08'$ (2000), and most part of the galaxy IC 1613 was located in the chip 51 of the WFI. We preferred not to apply the "dithering" mode in order to avoid contamination from a very bright star, which was placed in the gap between two chips.

Table 1. Log of observations.

Band	Night	Julian date
B	2000 Oct. 31	2 451 848.645
V		2 451 848.665
R		2 451 848.675
I		2 451 848.685
B	2000 Nov. 2	2 451 850.605
V		2 451 850.595
R		2 451 850.586
I		2 451 850.518
B	2000 Nov. 6	2 451 854.550
V		2 451 854.570
R		2 451 854.582
I		2 451 854.595
B	2000 Nov. 8	2 451 856.541
V		2 451 856.573
R		2 451 856.590
I		2 451 856.600
B	2001 Oct. 25	2 452 207.514
V		2 452 207.539
B	2001 Nov. 8	2 452 221.590
V		2 452 221.573
R		2 452 221.555

3. Data reduction

The reduction was performed using IRAF[1]; each chip was treated separately. The images were de-biased and flat fielded. Since the CCDs are backilluminated, the *I*-band images (both flat and stellar fields) were de-fringed before the flat field correction; a special image of the fringes elaborated by ESO was used for this process[2]. The subsequent procedure included the trimming for the elimination of the overscan areas, the alignement and the sum. The profile photometry of the stars was performed using DAOPHOT and ALLSTAR programs. The images of each chip were not divided in subframes since the point spread function (PSF) did not appear to change significantly across them; the χ^2 value of the PSF fitting changed on the average of few percent, with the best values far from the more (slightly) crowded regions. The PSF model was derived iteratively. About 15–20 relatively bright and isolated stars were selected and the first approximation model was calculated. In the next step we subracted all the neighbor stars with the ALLSTAR program and derived the PSF model again. The PSF model obtained after four such loops was finally adopted. At the end of the process, the total number of the detected stars was about 15 000. The standard stars observed in service mode were not sufficient for an accurate calibration of the various images in the various bands. Moreover, the application of the zero-point correction maps supplied by ESO was not sufficient to solve the problem of the large-scale intensity variations (e.g. Koch et al. 2004). Therefore we adopted the photometry of the fields observed by Cole et al. (1999) and Udalski et al. (2001) to tie directly the observations of our best night (November 6, 2000) to the standard system. Subsequently, we found some differences from night to night, that is field photometry distortions which could not be corrected for by simple zero-point corrections. We applied a fifth-order, bi-dimensional polynomial fit to the magnitude differences of the stars between the images of the best night (used as template) and those of the other nights. The full Table 2, available at the CDS, contains the *BVRI* photometry data of the 52 Cepheids (listed in Table 3), used for the discussion in the present paper.

Equatorial coordinates were calculated using a template extracted from the Digital Sky Survey (DSS) and an algorithm based on the two IRAF tasks CCMAP and CCTRAN. The first task computed the parameters of a second-order bi-dimensional polynomial, and the second task applied the transformation. The mean differences of right ascension and declination are $0\fs014$ and $0\farcs28$.

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

[2] `www.ls.eso.org/lasilla/sciops/2p2/E2p2M/WFI/CalPlan/fringing`

Table 2. *BVRI* photometry data of bright Cepheids (excerpt).

Number WFI	Band	JD-2 450 000	Mag	σ
1450-2	*B*	1848.645	20.156	0.010
1450-2	*B*	1850.605	20.257	0.009
1450-2	*B*	1854.550	20.246	0.014
1450-2	*B*	2207.514	19.464	0.015
1450-2	*V*	1848.665	19.188	0.010
1450-2	*V*	1850.595	19.217	0.008
1450-2	*V*	1854.570	19.237	0.014
1450-2	*V*	1856.573	19.209	0.021
1450-2	*V*	2207.539	18.642	0.013
1450-2	*V*	2221.573	19.052	0.010
1450-2	*R*	1848.675	18.452	0.008
1450-2	*R*	1850.586	18.499	0.009
1450-2	*R*	1854.582	18.582	0.013
1450-2	*R*	1856.590	18.500	0.010
1450-2	*I*	1848.685	18.022	0.011
1450-2	*I*	1850.518	18.041	0.014
1450-2	*I*	1854.595	18.155	0.014
1450-2	*I*	1856.600	18.128	0.019

Table 3. Intensity mean magnitudes of bright Cepheids in IC 1613.

Number WFI	Number OGLE	Number Wh	Period (days)	*B*	*V*	*R*	*I*
1450-2	11446	–	41.953	19.62	18.81	18.25	17.86
3059-3	1987	–	25.744	20.24	19.40	18.80	18.55
2885-3	736	C1311	23.466	19.99	19.26	18.77	18.45
4384-2	13738	A1039	16.424	20.62	19.99	19.53	19.11
6628-2	4861	B2952	12.412	20.94	20.29	19.82	19.45
3191-2	7664	B4697	10.4327	20.47	20.07	19.65	19.42
1323-3	926	C1193	9.4303	20.89	20.30	19.91	19.64
1046-3	879	C1638	9.2114	20.84	20.24	19.88	19.60
1481-2	11589	B1274	8.4785	21.24	20.72	20.26	19.99
3384-2	13808	A2414	7.573	21.50	20.94	20.46	20.17
5159-2	18905	–	6.783	21.56	21.03	20.52	20.23
4534-2	13943	A1337	6.7428	20.97	20.51	20.24	19.96
0193-2	3732	D0078	6.6605	21.26	20.68	20.31	20.06
2548-2	5037	B0848	6.399	21.95	21.04	20.78	20.29
1638-2	11604	–	5.832	21.92	21.28	20.71	20.49
0127-2	3722	D0024	5.8188	21.59	21.00	20.50	20.29
4175-2	13911	A1734	5.7364	21.12	20.69	20.35	20.17
7651-2	–	B4540	5.592	21.20	20.75	20.51	20.35
3171-2	13780	A0819	5.5786	21.60	20.99	20.56	20.37
1535-2	4875	B0129	5.1446	21.29	20.91	20.45	20.25
1057-2	11831	–	5.047	22.04	21.47	20.95	20.76
5679-2	15696	–	5.040	21.76	21.25	20.89	20.56
5448-2	15670	–	4.844	21.32	20.95	20.59	20.39
6715-2	5574	B0177	4.8295	22.19	21.51	21.07	20.72
8284-2	14287	A1592	4.3606	22.27	21.65	21.41	20.89
1242-1	18891	–	4.2836	21.77	21.30	20.97	20.68
7046-2	7919	B0926	4.2693	21.77	21.37	20.84	20.73
6076-2	12415	–	4.249	21.87	21.41	21.05	20.80
2231-2	5857	B3062	4.2272	21.58	21.20	20.59	20.52
1687-2	12109	–	4.125	21.91	21.36	20.92	20.76
6157-2	13784	A1897	4.0638	21.28	21.03	20.72	20.45
0908-3	1132	C0347	4.0189	22.00	21.55	21.10	20.83
3427-2	8127	–	3.839	22.17	21.61	21.23	20.86
7323-2	18222	–	3.800	–	21.65	21.06	21.03
3839-2	14356	A2256	3.6624	21.94	21.45	21.08	20.82
0582-3	961	C0031	3.6348	22.31	21.81	21.38	21.05
6746-2	5614	B1720	3.4301	22.41	21.90	21.59	21.16
8609-2	5611	B2991	3.261	22.11	21.63	21.24	20.96
2047-2	5750	B2560	3.233	–	21.76	21.20	21.12
2214-2	–	B1995	3.239	22.48	21.63	21.45	21.20
1663-3	2240	–	3.0733	22.19	21.60	21.24	21.10
0427-3	342	–	3.0772	22.11	21.63	21.41	21.09
8103-2	6273	B2050	3.025	22.22	21.75	21.38	21.11
0540-2	4016	D0512	2.9871	22.65	22.13	21.65	21.45
4313-2	–	A1014	2.9501	–	21.97	21.63	21.40
4613-2	18349	A0555	2.86904	21.93	21.71	21.34	21.14
6302-2	19024	–	2.843	22.28	21.85	21.46	21.14
8555-2	16011	–	2.814	23.01	22.11	21.59	–
1959-2	12233	B3782	2.7930	22.61	21.86	21.76	21.18
6650-2	12068	–	2.781	22.67	21.88	21.70	21.47
1699-3	2760	–	2.712	22.38	21.86	21.48	21.30
0717-3	1471	C0907	2.7037	22.32	21.94	21.42	21.32

4. Cepheids

The Cepheids are reported in Table 3. The stars are identified with the numbers: a) "WFI", that is the number in the catalog for each of the three chips (1, 2 and 3) that contained the galaxy fields; b) "OGLE" of Udalski et al. (2001); c) "*Wh*" of our previous Papers I, III and IV. The table includes the improved period P and the mean *BVRI* magnitudes, that were obtained with the procedure described in the following. Of the 138 OGLE Cepheids, 104 objects were identified in our WFI images. Several unidentified stars were located in the gaps between the chips, while for three stars the identification was not possible since the maps supplied by OGLE did not correspond to a variable star position. Table 3 includes only the 52 stars that are considered fundamental mode Cepheids with $P \gtrsim 2.7$ d, on the basis of their P and light curve shape (Fourier parameters). Cepheids with shorter period are excluded in order to avoid contamination with first overtone mode pulsators, and owing to the decreasing level of accuracy in the resulting photometry of fainter stars. The star OGLE 4840 with $P = 4.01$ d was also excluded since the multicolor photometry indicated that it should be a red variable.

Firstly the V band WFI and OGLE data were merged together. It resulted that four WFI observations were performed during the OGLE observing run itself, while the other two WFI observational data were taken one year apart. In general, the fitting of the light curves did not show large discrepancies in the V band, except for some data points or stars that resulted generally to be fainter than OGLE ones. An estimate was done of the possible transformation from *Wh* to V band light curves for the Cepheids observed in both bands, according to the Freedman's method. We have found that, on the average the amplitude must be divided by a factor 0.83 and a small phase shift of about 0.02 was considered. The examples of the phased data shown in Fig. 1 indicates that the procedure is acceptable. The P of the stars was generally improved by the merging of V and *Wh* band data. In some cases we have checked the possibility of merging also the old photographic data, and we decided to adopt the new P values only in the case of the Cepheids with the longest P.

The mean intensity values of the *BVRI* magnitudes were derived as follows. The V light curves of stars with OGLE and WFI data were Fourier analysed. The resulting V mean values in Table 3 are therefore not very different from those reported by Udalski et al. (2001). The V (WFI) and *Wh* band data of four stars with no OGLE data were used to construct a V light curve, that was Fourier analysed in order to get the mean intensity value. The subsequent step was the estimate of the B and R mean intensity values for all the 52 Cepheids. We adopted the amplitude ratios $V/B = 0.67$ and $R/V = 0.66$ and phase shifts 0.03 (B, V) and 0.04 (V, R) (Freedman 1988). The resulting mean values are not very sensitive to such adopted values, showing that the Freedman's method is quite robust. As regards the I band data, the quality of the WFI photometry turned out to be not very high, therefore we preferred to adopt the mean intensity values published by Udalski et al. (2001). The I (WFI) data were used for three stars for which the OGLE

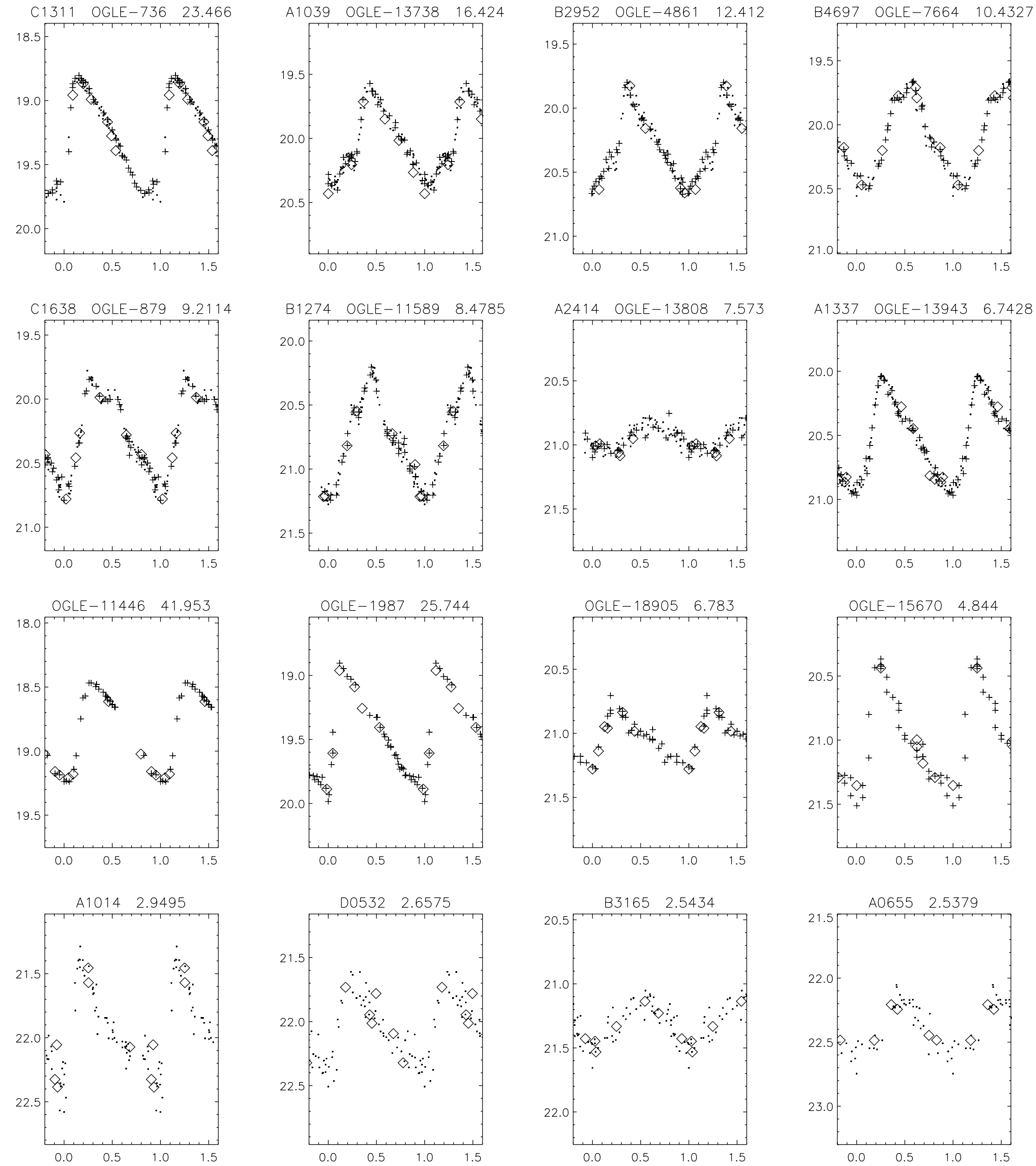

Fig. 1. V-band light curves of a sample of Cepheids with relatively long period in IC1613; *diamonds*: WFI data, *plus*: OGLE data; *dots*: Wh-band data converted to V-band. In each panel, an identification label and the period in days is reported. The first two rows show Cepheids observed both in the Wh band and by OGLE, the subsequent row show Cepheids detected by OGLE, and the last row shows some relatively faint Cepheids which were not detected by OGLE or with no OGLE V-band data.

data were lacking. In this case we adopted a ratio $I/V = 0.51$ and a phase shift of 0.07.

5. P-L diagrams

The main characteristics of the P-L diagrams, shown in Fig. 2, are those expected, that is the slope increases with the wavelength and the dispersion decreases with the wavelength. The formal P-L relations are the following:

$$B = -2.48(\pm.16)(\log P - 1.) + 20.99(\pm.06) \quad (1)$$

$$V = -2.70(\pm.10)(\log P - 1.) + 20.38(\pm.04) \quad (2)$$

$$R = -2.85(\pm.10)(\log P - 1.) + 19.94(\pm.04) \quad (3)$$

$$I = -2.94(\pm.07)(\log P - 1.) + 19.64(\pm.03). \quad (4)$$

As a comparison, the slopes of the relations for the BVI bands of the LMC Cepheids derived from OGLE data by Sandage et al. (2004) are −2.34, −2.70, and −2.95, respectively. The magnitudes must be corrected for the reddening, which is known to be rather small. We have tried to use the method of Madore & Freedman (1991) and the above relations to get an independent estimate. The model for the interstellar reddening of Cardelli et al. (1989) was considered, along with a value of $R = A_V/E(B-V) = 3.2$, and with LMC as a reference. That is, the LMC absolute magnitude $BVRI$ P-L relations of Madore & Freedman (1991) were adopted. Formally, we got

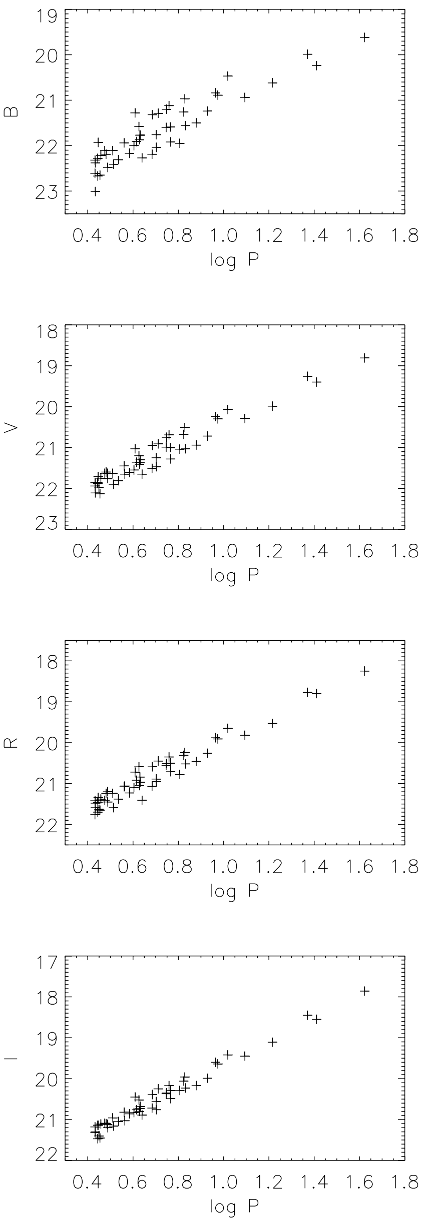

Fig. 2. P-L diagrams for the *BVRI* bands of Cepheids in IC 1613.

μ_0(IC 1613) = 24.23 (±.20) and $E(B-V) = 0.068$ (±.075). The reddening is very uncertain. The method is not very robust since it is based on the differences between the coefficients of the P-L relations that have significant uncertainties. An improvement would be to fix the "universal" slope of the P-L relations, and this is closer to the method used by Madore & Freedman (1991). Using only the *BVI* data and the relations given by Sandage et al. (2004), we got $E(B-V) = 0.024(\pm.030)$, while using only the *VI* data and the relations given by Udalski (2000) we got $E(B-V) = 0.044(\pm.049)$. The formal uncertainty is always similar to or larger than the reddening value itself. The reddening estimate will be improved when additional near-infrared photometry of Cepheids in IC 1613 will become available (Pietrzynski et al. 2005). For the present we will adopt the less uncertain value, 0.024. Since in the following we will compare our results with those of Tammann et al. (2003) and Sandage et al. (2004), we will use μ_0(LMC) = 18.54 and their *BVI* P-L relations. The corresponding distance modulus is μ_0(IC 1613) = 24.50(±.12).

6. Instability strip, P-C and color–color diagrams

The absolute V magnitude is plotted against $(B-V)_0$, $(V-R)_0$ and $(V-I)_0$ in Fig. 3. The distribution of the stars of IC 1613 can be compared with the instability strip of LMC indicated by Sandage et al. (2004) for the color indices $(B-V)_0$ and $(V-I)_0$. The continuous line is the ridge line of the LMC instability strip, and the dotted lines indicate approximately the distribution of about 90% of LMC Cepheids. The $(V-I)_0$ plot does not show large differences between LMC and IC 1613, perhaps apart from the verticality of the lower part of the instability strip. The $(B-V)_0$ plot shows some scatter for short period Cepheids. We think the five stars with $(B-V)_0 \gtrsim 0.7$ and low luminosity are too red and must be considered as outliers (possible contaminations or lower photometric accuracy). Taking into account the position of the brightest Cepheids, the stars of IC 1613 are generally bluer than those of LMC, at a given absolute magnitude (or period), a result that could be explained by the lower metallicity of IC 1613. On the whole, the lower part of the instability strip ($M_{V_0} \gtrsim -4.2$) of IC 1613 looks more vertical than that of LMC. It is interesting to note that the IC 1613 Cepheids are intrinsically bluer than their LMC counterparts in $(B-V)$, but not so in $(V-I)$. This contrast seems important for the selection of bandpasses to be used in extragalactic distance scale work with Cepheids: it argues for the universality of Cepheid P-L relations in V and I, and cautions against the use of a combination of B and V P-L relations.

The period–color P-C diagrams are shown in Fig. 4. The comparison with the LMC P-C relation reported by Sandage et al. (2004) suggests that the distribution of the IC 1613 stars could be compatible with a break of the P-C relation at $P \sim 10$ d analogous to the LMC one. The few stars with $P > 10$ d do not allow to verify whether also the P-L relations are compatible with the possible break observed in LMC. The $(B-V)_0$ plot suggests a systematic difference with respect to the LMC P-C relation; this is more evident if we exclude the five "red" outliers.

Finally, the $(B-V)_0$ vs. $(V-I)_0$ diagram is shown in Fig. 5, where the distribution of IC 1613 stars is compared with the mean position of Cepheids in LMC (dotted line) and SMC (continuous line) taken from Tammann et al. (2003). The Cepheids of IC 1613 are more similar to those of SMC; those with longest P suggest an even larger separation from the LMC line than that of SMC. The P-C and color–color diagrams indicate therefore systematic differences between IC 1613 and the Magellanic Clouds. They could be explained by the lower metallicity of IC 1613. The uncertainties on the reddening estimates do not affect these conclusions.

7. Conclusion

A few WFI *BVRI* observations have been used to derive multicolor data of Cepheids identified in previous surveys of IC 1613. The method of Freedman (1988) has been applied to get reliable mean intensity values of Cepheid magnitudes in the

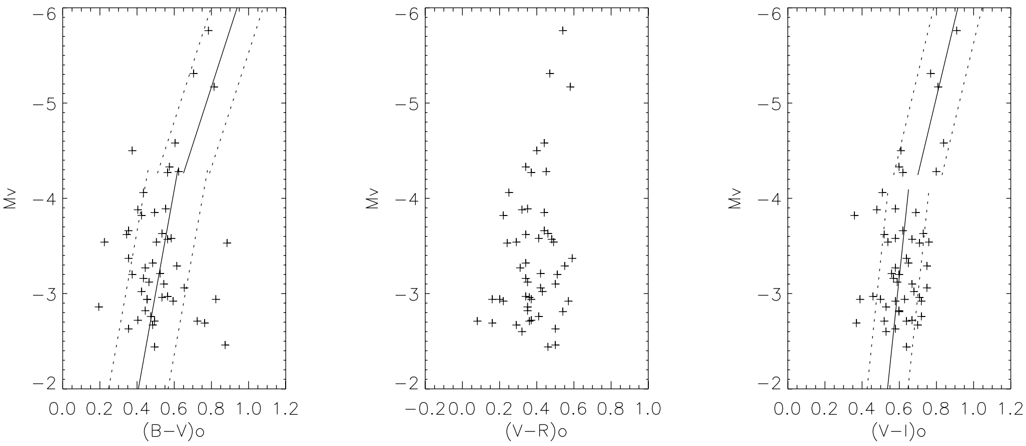

Fig. 3. Dereddened color–magnitude diagrams showing the position of Cepheids of IC 1613 compared with the instability strip of LMC (see text).

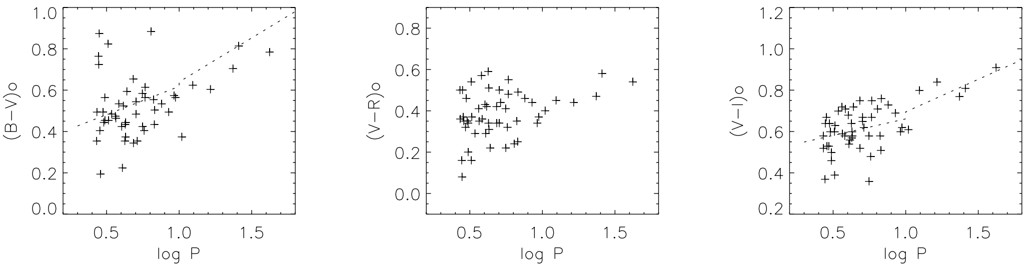

Fig. 4. Dereddened P-C diagrams showing the position of Cepheids of IC 1613 in comparison with the P-C relation of LMC stars (dotted line).

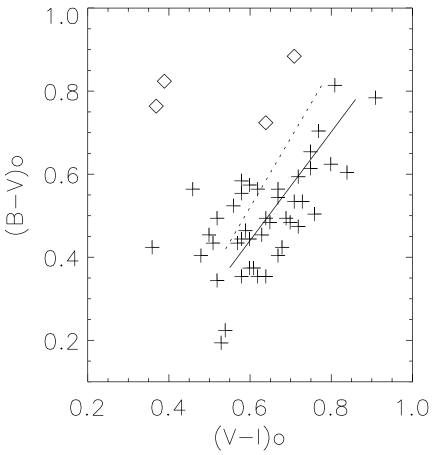

Fig. 5. $(B-V)_0$ vs. $(V-I)_0$ diagram. The position of Cepheids of IC 1613 is compared with the mean position of LMC (dotted line) and SMC (continuous line) stars. The diamonds are the low luminosity stars with too red $(B-V)_0$ color index.

various bands. The method appears to be rather robust, and it is worth to extend it to other galaxies. Moreover, it would be worth to better define the shorter period part of the P-L relations by means of few deeper WFI observations. The slopes of the *BVI* P-L relations obtained in the present work are consistent, within the uncertainties, with those previously obtained by other authors for LMC. The distribution of the Cepheids in the period–color diagrams is compatible with a change near $P \sim 10$ d as was suggested for LMC. The distribution in the diagrams is more similar to that in the SMC, and this should be related to the very low metallicity of the galaxy.

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