

Letter to the Editor

A Photometric Determination of the Metal Content for Cepheids in the Small Magellanic Cloud*

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Summary. The metal-index $[B-L]$ in the Walraven VBLUW photometric system is used to study Cepheids in the Magellanic Clouds. This metal-index is reddening-independent, and in the temperature range reached by most Cepheids around maximum light, also practically independent of effective temperature and surface gravity. By comparing the first results for 8 SMC Cepheids with extensive VBLUW data on galactic Cepheids, and with theoretical colours based on model atmospheres by Kurucz, we find a mean metallicity $[Fe/H] = -0.70 \pm 0.25$ for the SMC variables. Application of a galactic P-L-C-relation to SMC Cepheids, without taking the low SMC metal (and helium) content into account, could result in an overestimate of Cepheid luminosities and distance moduli in the SMC by about 0^m48.

Key words: Cepheids - Magellanic Clouds - metal content - multicolour photometry

1. Introduction

The evidence for low abundances of helium and heavier elements in the Magellanic Clouds has been growing rapidly during the last decade (cf. Peimbert, 1975; Dufour, 1975; Aller et al., 1977; Webster, 1978; Pagel et al., 1978), indicating heavy-element deficiencies relative to the Sun of up to a factor 10 in the Small Cloud (SMC) and a factor 2 or 3 in the Large Cloud (LMC). These results refer almost exclusively to gaseous nebulae, however, and quantitative data on the composition of stars in both Clouds are still very scarce.

This situation is particularly unsatisfactory for the Cepheid variables, where the Magellanic Clouds have a key position in the calibration of intrinsic properties and distances. Although it has long been known that there are probably intrinsic differences in the colours and in the statistics of periods and amplitudes between the Cepheids of SMC, LMC, and Galaxy (Gascoigne, 1969; van Genderen, 1969, 1978; Payne-Gaposchkin, 1971), and several authors have interpreted these differences in terms of chemical composition (e.g. Bell and Parsons, 1972; Robertson, 1973; Gascoigne, 1974; Iben and Tuggle, 1975; Becker et al., 1977), direct information on the composition of Magel-

lanic Cloud Cepheids has become available only very recently (Harris, unpublished, as reported by Wallerstein, 1980). The observations by Harris, in the Washington photometric system, suggest $[Fe/H] \approx -0.5$ to -0.7 for the SMC Cepheids.

In the present paper we report first results from photometry of SMC Cepheids in the Walraven VBLUW system (for passbands see Table 1). This system, although originally designed for the study of OB-stars (Walraven and Walraven, 1960), has turned out to be very useful at lower temperatures (Lub and Pel, 1977, "LP"), and it has been used in large programmes on galactic Cepheids and RR Lyrae stars (Pel, 1976, 1978; Lub, 1977, 1979). From these studies it became clear that the reddening-free colour $[B-L]$ is a very powerful metal-index for F and G stars, with particularly attractive properties for Cepheids (Pel and Lub, 1978, "PL"). After the move, in 1979, of the Leiden 91-cm reflector and the Walraven photometer from the Leiden Station at Hartebeespoortdam (South-Africa) to ESO (La Silla, Chile), high priority was therefore given to VBLUW photometry of Cepheids in the Magellanic Clouds.

Table 1. Effective wavelengths and bandwidths (in Å) of the VBLUW passbands

	V	B	L	U	W
λ_{eff}	5467	4325	3838	3633	3255
BW	719	449	227	239	143

2. Observations

Van Genderen (1977) had already obtained VBLUW photometry for a number of Cepheids in the core of the SMC. He found a pronounced blue and ultraviolet excess for these Cepheids as compared to their galactic counterparts. The quality of his data was however hampered by crowding problems, mostly due to the fact that poor seeing at Hartebeespoortdam did not allow the use of small diaphragms. In this respect, the excellent seeing conditions on La Silla meant a big improvement. Moreover, during the move of the 91-cm telescope to its new site, the VBLUW photometer was improved in several respects, and a large gain in ultraviolet sensitivity was obtained.

For the new VBLUW programme on SMC/LMC Cepheids we selected in each Cloud 20 variables. They were chosen outside the dense central regions, and checked carefully to be free from disturbing companions. As will be explained in the next section, the domain of $[B-L]$

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most favourable for metallicity determinations is reached by shortperiod Cepheids around maximum light. The periods were therefore restricted to $P < 15^d$, and each variable was observed at maximum. Long integrations were used to ensure sufficient accuracy in the L and U channels (altogether 30 min. star, 30 min. sky). Up-to-date maximum epochs were determined from a few shorter integrations at arbitrary phases. An 11"6 diaphragm was used, and the measurements were made only on dark nights with good seeing. All observations were made with the five-channel photometer attached to the 91-cm Dutch Telescope at ESO. In this paper we report first results on 8 SMC Cepheids, obtained during the period September-October 1979. General information on these variables is listed in Table 2.

Table 2. General information on the SMC Cepheids discussed in this paper

Star	P	maximum B_{UBV}	amplitude B_{UBV}
HV 843	14. ^d 7	15. ^m 2	1. ^m 5
1345	13.5	14.8	1.0
1744	12.6	14.4	1.3
1365	12.4	15.1	1.3
1610	11.6	14.6	1.5
2063	11.2	15.0	1.3
1768	9.8	15.3	0.4
1374	8.4	15.4	0.9

3. Method and Results

The method is based on the $[B-L]-[L-U]$ diagram introduced in PL (Fig. 1). $[B-L] \equiv (B-L) - 0.43(V-B)$ and $[L-U] \equiv (L-U) - 0.21(V-B)$ are reddening-independent indices. All data in Fig. 1, the observations as well as the theoretical colours, have been reduced to the 1970-1978 VBLUW system by means of small transformation corrections that allow for the small differences between the Hartebeespoortdam and La Silla Systems.

Fig. 1a gives the theoretical colours computed in LP from the model atmosphere fluxes of Kurucz (1979). Only the cooler part of the grid is shown. The zeropoints of the colours in Fig. 1a are determined by fitting the solar-composition grid to the observed population-I main-sequence. This fit produces zeropoints that differ slightly (+0.019 in $[B-L]$, -0.017 in $[L-U]$) from the zeropoints implied by Table 12 of LP, and used in Fig. 1 of PL (in the latter diagram the *observations* were shifted by -0.019 and +0.017 to match the theoretical colours of LP, whereas in the present diagram the theoretical colours were shifted). For a clear understanding of the following discussion we point out that by fixing the zeropoints in Fig. 1a by means of pop.-I stars (rather than by stars of various compositions) we use the theoretical colours only in a differential sense with respect to the solar-composition grid.

The important features of Fig. 1a can be summarized as follows:

- a) In the temperature range 5500-7000 K, $[B-L]$ is very sensitive to the line-blocking by heavy elements in the L band. Above 6000 K this blocking is almost entirely due to metals, mostly Fe; the composition dependence of $[B-L]$ is therefore directly related to $[Fe/H]$. $[L-U]$ is very insensitive to metal content.
- b) For a given composition, the intrinsic lines have a sharp blue boundary in $[B-L]$. Along this boundary $[B-L]$ is nearly constant. We therefore obtain a reddening-, temperature-, and gravity-independent measure for

$[Fe/H]$ from $[B-L]$ at the blue boundary, provided that this boundary can be located from observations.

The attractive possibilities of the $[B-L]-[L-U]$ diagram that are thus predicted theoretically, obviously need observational confirmation. A first check is made by a number of metal-poor subdwarfs (triangles in Fig. 1b, data from LP). By comparing the VBLUW data with spectroscopic values of T_{eff} and $[Fe/H]$ for these stars, we find that the composition effects in Fig. 1a have the right direction and size. E.g. for the most extreme subdwarfs in Fig. 1b, HD19445 at $[B-L] = 0.053$ and HD140283 at $[B-L] = 0.057$, Carney (1979) gives $[Fe/H] = -2.12$ and -2.60 . For these same subdwarfs, the Kurucz colours in Fig. 1a predict $[Fe/H] = -2.7$ and -3.0 . The latter values are lower than the spectroscopic results, but they indicate that the theoretical and observed blanketing effects in $[B-L]$ in this temperature range agree to within 10%. At higher temperatures, Lub (1979) has used $[B-L]$ as a metal-index for RR Lyrae variables, and he has shown that calibration of $[B-L]$ by means of the Kurucz model leads to consistent results for $[Fe/H]$.

A sensitive test of our method to derive the metal content is provided by the population-II Cepheid UY ERI. As discussed already in PL, the loop described by this variable in Fig. 1b fits in detail to the theoretical $[B-L]-[L-U]$ colours for $[Fe/H] = -1.50$ ($A = 0.03$). Adopting now $A = 0.03$, we can derive the detailed temperature and gravity variations of UY ERI in the theoretical (V-B)-(B-U) diagram of LP. Going one step further, we can compute the radius variations of UY ERI from its lightcurve, and from the temperatures and bolometric corrections derived from the Kurucz colours. The fact that the resulting radius and gravity curves have a realistic shape, phase and amplitude, is a sensitive test on the reliability of Fig. 1a. The gravity curve in particular depends strongly on the adopted value of A . With $A = 0.03$ we find a curve that peaks at the correct phase, just before maximum light. The curve has a total amplitude of 0.65, and a mean level of $\log g = 2.30$. Interpreting UY ERI as a classical Cepheid with $A = 1$, would have led to a very high mean gravity (3.15) and a strongly distorted gravity curve which is in no way compatible with the pulsation behaviour (e.g. no pressure peak on the rising branch).

Before turning to the SMC, let us discuss briefly the behaviour of galactic Cepheids in Fig. 1. Fig. 1b gives the maxima of 131 classical Cepheids with accurate U data from Pel (1976) and Walraven et al. (1964). We can draw the following conclusions (see also PL, Fig. 1):

- 1) The blue $[B-L]$ -boundary for $A = 1$ is reached only by the hottest Cepheid maxima, with $T_{\text{max}} \geq 6500$ K. Such hot maxima occur at the shortest periods, and at $P = 10-15^d$, due to the large amplitudes in the latter interval. At any given period, T_{max} scatters sufficiently to cover a wide range in $[L-U]$, but in general $[L-U]_{\text{max}}$ decreases with increasing P .
- 2) The locus of "normal" maxima (see caption Fig. 1) coincides with the region outlined by the complete loops of the Cepheids. If we adjust the $A = 1$ grid to the higher microturbulence of 4 km s^{-1} that seems appropriate for supergiants, the locus runs roughly from the point (7000 K, $\log g = 2.5$) to (5500 K, 1.5).
- 3) 23 maxima lie outside the locus, but 18 of these are from "peculiar" Cepheids, with evidence for companions or composition anomalies (see Pel, 1978). The double-mode Cepheids in Fig. 1b behave like normal shortperiod Cepheids.
- 4) The width of the locus indicates a spread in metal content of $\leq \pm 20\%$ around the solar value. This may seem a surprisingly small range in view of the composition gradients that probably exist in the Galaxy, but it

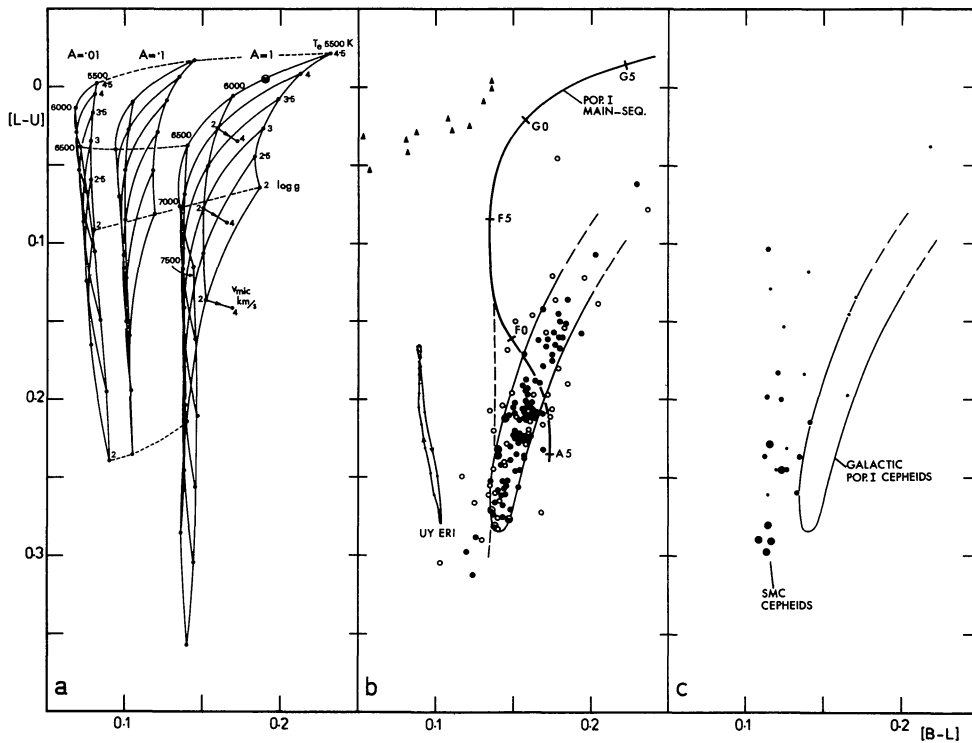


Fig. 1. The $[B-L]$ - $[L-U]$ two-colour diagram. Both colours are in $\log(\text{intensity})$, so 0.1 in the diagram corresponds to 0.25^m .

a) Theoretical colours computed by Lub and Pel (1977) from the model atmosphere fluxes of Kurucz (1979). $A = 1, 0.1, 0.01$ correspond to $1\times, 0.1\times,$ and $0.01\times$ the solar heavy-element content. Dashed lines indicate the blanketing vectors for a few selected gridpoints. Arrows labeled $2 \rightarrow 4$ show the effect of raising the microturbulence from 2 to 4 km s^{-1} for three 6000 K models in the $A = 1$ grid. The solar model is indicated by \odot .

b) \blacktriangle : metal-poor subdwarfs
 \bullet, \circ, \odot : maxima of galactic population-I Cepheids
 \bullet : "normal" Cepheids, i.e. no signs of companions or composition anomalies
 \circ : "peculiar" Cepheids, with evidence for companions or non-solar composition
 \odot : highest maxima of double-mode Cepheids

The locus of "normal" Cepheid maxima is indicated by a thin line, the A5-G5 population-I main-sequence by a heavy curve, and the blue $[B-L]$ -boundary of the theoretical $A = 1$ colours by a vertical dashed line. The closed loop for UY ERI shows the entire cycle of this population-II Cepheid.

c) Observations near maximum light of 8 SMC Cepheids, together with the locus of galactic Cepheid maxima. Relative weights are indicated by the size of the dots (see Section 3).

should be noted that practically all Cepheids in our sample lie within 8-11 kpc from the galactic centre.

The results on SMC Cepheids are shown in Fig. 1c. As not all 8 Cepheids could be observed exactly at maximum, the diagram contains also observations at phases near maximum light. The largest dots in Fig. 1c have highest weight, and correspond to observations very close to maximum. Smaller weights are assigned to observations further away in phase, indicated by smaller dots. The data with lowest weight have rather low photometric accuracy, especially in $[L-U]$. It is remarkable that we obtain again a well defined "maximum locus" in Fig. 1c. The more significant SMC observations define a region which is hardly wider in $[B-L]$ than the locus of galactic maxima, and which is clearly displaced towards lower $[B-L]$. Like in the galactic locus, the highest values of $[L-U]$ are reached by the 10-15^d Cepheids.

From the position of the SMC locus in Fig. 1c we estimate that the corresponding blue $[B-L]$ -boundary lies

$0.024 (= 0.06^m)$ to the left of the boundary for $A = 1$. This is assuming that galactic and SMC Cepheids have the same microturbulence, and that the effects of microturbulence at lower values of A scale proportionally to the blanketing vectors in Fig. 1a. The calibration of Fig. 1a then leads to $[\text{Fe}/\text{H}] = -0.70$ for the SMC Cepheids. Again we stress that this value has been determined *relative* to population-I stars in the solar neighbourhood. The accuracy of this result is determined by the photometric accuracy, uncertainties in the fit of observed and theoretical colours, and systematic errors in the calibration. The first two sources together introduce an uncertainty in the position of the SMC blue $[B-L]$ -boundary of about ± 0.005 in $[B-L]$, which corresponds to ± 0.15 dex in $[\text{Fe}/\text{H}]$. The systematic uncertainties in Fig. 1a are very difficult to evaluate, but from the various checks on the calibration discussed above we estimate that in the domain of the Cepheid maxima the Kurucz models predict abundances with an accuracy of about ± 0.20 dex. This means an overall uncertainty in our $[\text{Fe}/\text{H}]$ value of about ± 0.25 dex.

4. Discussion

The above results confirm the differences in VBLUW colours between galactic and SMC Cepheids reported previously by van Genderen (1977); they also support similar colour effects found in other photometric systems (e.g. Gascoigne, 1969, Wallerstein, 1980). Composition is not the only possible cause of these colour differences, however. An alternative has been proposed by DeYoreo and Karp (1979), who ascribe the blueness of SMC Cepheids to contamination by companions. Such an explanation is not supported by the data in Fig. 1: although most "peculiar" Cepheids in Fig. 1b are stars with evidence for companions, their mean position is hardly different from the locus of normal maxima. The SMC colours in Fig. 1c are therefore hard to explain by companions.

Our value $[Fe/H] = -0.70$, i.e. a metal deficiency of a factor 5 with respect to the Sun, agrees within the uncertainties with the result from Harris' photometry of SMC Cepheids (Wallerstein, 1980), and with the calcium abundance determinations by Smith (1980) for non-pulsating F supergiants in the SMC. At this stage we will make only a rough estimate of some consequences of such a low metal content; before making a detailed analysis, we prefer to collect more data on a larger sample of SMC Cepheids.

Gascoigne (1974) has pointed out that Cepheid luminosities and distances as derived from a period-luminosity-colour (P-L-C) relation depend strongly on the adopted heavy-element abundance Z , due to the Z -sensitivity of the mass-luminosity (M-L) and colour-temperature (C-T) relations for Cepheids. Although we really have information only on the abundance of Fe and iron-peak elements, let us assume that the low value of $[Fe/H]$ applies also to the overall heavy-element abundance Z of the SMC Cepheids. Adopting $Z = 0.004$ ($[Fe/H] = -0.70$), we can then follow Gascoigne's argument, and make new estimates by means of improved M-L and C-T relations. For the latter we take again the theoretical VBLUW colours of LP, and find that the temperature of an average 10^d Cepheid is overestimated by 290 K, if the C-T relation for $Z = 0.02$ is applied to Cepheids with $Z = 0.004$. This means that L derived from period, colour, and a "solar" P-L-C relation, is overestimated by 0^m28 . To this we should add the effect of Z on the P-L-C relation via the M-L relation. Using the composition dependence of the Cepheid M-L relation as computed by Becker et al. (1977), we find that L of the same 10^d Cepheid decreases by 0^m29 when Z is lowered from 0.02 to 0.004. Application of a "solar" P-L-C relation to SMC Cepheids with $Z = 0.004$ would therefore produce luminosities and distance moduli that are too high by $\sim 0^m57$.

We stress that this number is only a first approximation. The effect of Z on the bolometric corrections is not included, because the Kurucz data in LP indicate that this is small. More important corrections are probably necessary, however, because also helium seems underabundant in the SMC (Peimbert and Torres-Peimbert, 1974, 1976). Becker et al. predict that the effect on L of a low Z is partly compensated by the opposite influence of a low helium abundance: a decrease of Y for the SMC Cepheids from 0.28 to 0.24, as suggested by Fig. 2 of Lequeux et al. (1979), reduces the luminosity correction from 0^m57 to 0^m48 . To what extent the SMC distance modulus will be affected by adjustments of the luminosities of SMC Cepheids, can only be determined from a careful discussion of all distance indicators in

the SMC. We do not intend to present such a discussion here, but it is clear that the Cepheids, which are probably the most accurate distance indicators, have high weight in the final determination of the SMC distance.

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