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Metallicity estimates of Galactic cepheids based on Walraven photometry

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Abstract. We present new empirical and theoretical calibrations of two photometric metallicity indices based on Walraven photometry. The empirical calibration relies on a sample of 48 Cepheids for which iron abundances based on high resolution spectra are available in the literature. They cover a broad range in metal abundance (-0.5 ≤[Fe/H]≤+0.5) and the intrinsic accuracy of the Metallicity Index Color (MIC) relations is better than 0.2 dex. The theoretical calibration relies on a homogeneous set of scaled-solar evolutionary tracks for intermediate-mass stars and on pulsation predictions concerning the topology of the instability strip. The metal content of the adopted evolutionary tracks ranges from Z = 0.001 to Z = 0.03 and the intrinsic accuracy of the MIC relations is better than 0.1 dex.

Key words. Stars: Cepheids – abundances – atmospheres – variable stars

1. Introduction

Classical Cepheids present several advantageous features when compared with field giant stars. These are illustrated by the points below: *Distance indicators* – they obey to well defined optical and near-infrared (NIR) Period-Luminosity (PL) relations and their distances can be estimated with an accuracy of the order of a few percent (Benedict et al. 2006; Marconi et al. 2006; Natale et al. 2007; Fouque

Send offprint requests to: S. Pedicelli et al. 2007). They are also the most popular primary distance indicators to calibrate secondary indicators such as the SN type Ia (Riess et al. 2005). *Stellar tracers* – they are distributed across the Galactic disk, and therefore, they can be adopted to trace the radial distribution of intermediate-age stars (Kraft & Schmidt 1963). In particular, they provide robust constraints on the iron and heavy elements radial gradients (Lemasle et al. 2007, and references therein). *Bright stars*– they are bright giants that can be easily identified due to their intrinsic variability and for which accurate photometric and spectroscopic data can be collected. However, Classical Cepheids also present a few drawbacks. *Short lifetime* – the lifetime they spend inside the instability strip is approximately two orders of magnitude shorter than the central hydrogen burning (Bono et al. 2000). This together with the low spatial density and the high reddening account for the limited sample of Galactic Cepheids currently known (Fernie et al. 1995). *Time series* – Accurate mean magnitudes and colors require a detailed time sampling along the pulsation cycle. The Cepheid periods range from a few days to hundred days. Therefore, well sampled multiband light curves require long observing runs. In this investigation we decide to take advantage of the Walraven photometry for 174 Galactic Cepheids collected by Pel (1976) and by Lub & Pel (1977). The Walraven VBLUW photometric system was originally designed to derive the intrinsic properties of early-type stars. The bands were selected to measure the features of the hydrogen spectrum, and three of the five bands are located in the ultraviolet spectral regions (λ_V =5405 Å, λ_B =4280 Å, λ_L =3825 Å, λ_U =3630 Å, λ_W =3240 Å). The reader interested in a more detailed description concerning the ingenious crystal optics filter and the instrumentation is referred to Walraven & Walraven (1960), Lub & Pel (1977), and to Pel & Lub (2007). Because of its sensitivity to the Balmer jump and the slopes of the Balmer and Paschen continua, the Walraven system turned out to be also very useful for determining the intrinsic parameters of A, F, and G-type stars. For this reason, it has been used for the study of Galactic and Magellanic Cepheids (Pel 1976; Pel et al. 1981) and for field RR Lyrae stars (Lub 1977). Observations with the Walraven five-channel photometer, attached to the 91-cm 'Lightcollector' reflector, started in 1958 at the Leiden Southern Station in Broederstroom, South-Africa. After 20 years in South-Africa the telescope and the photometer were moved to ESO/La Silla in Chile. The observations in the new site started in March 1979 and continued for a dozen years until the decommissioning of the photometer in 1991. Thanks to the better photometric conditions of La Silla, this last phase of the operational life of the instrument was particularly fruitful. During 32 years of almost uninterrupted observations, a very large amount of high-quality data was obtained for many types of stars, but the emphasis was on OB-associations, clusters, Galactic and Magellanic Cepheids (~ 200), Galactic RR Lyrae stars (~ 100) and faint F/G stars in the disk and in the inner Galactic halo.

2. Data and theory

The current Cepheid sample was selected from the observing runs 1962 (Walraven et al. 1964) and 1970-1971 (Pel 1976) at the Leiden Southern Station (South Africa). The sample includes 174 Galactic Cepheids and it is 82% complete for all known Cepheids brighter than V = 11.0 mag at minimum and south of declination +15°. Fig. 1 shows the light curves in the five bands for three Cepheids of our sample, namely FW LUP, RZ VEL and RS PUP. Data plotted in this figure show that individual simultaneous VBLUW measurements present an accuracy of the order of few millimag. For each object have been collected at least 30 phase points that properly cover the entire pulsation cycle. This means that the intrinsic accuracy of the mean magnitudes estimated by fitting a cubic spline is of the order of a few hundredths of magnitude.

In order to constrain the possible occurrence of systematic errors in the optical photometry we are also collecting accurate multiband J, H, K NIR data. At present, accurate NIR data are available for 65 Cepheids in the Walraven sample. For these data the uncertainties of each phase point range from

0.005 to 0.007 for $K < 6$ mag, deteriorating to about 0.012 at $K = 8.6$. This implies an accuracy in the mean magnitudes of about 0.002 – 0.005, depending on the number of points. However, the dominant uncertainty on the mean magnitudes is probably due to the absolute calibration which is 0.01. For the other Cepheids we use the mean NIR magnitudes from the 2MASS catalog (Cutri et al. 2003). Fig. 2 shows the J, H and K-band light curves for four Cepheids in our sample. In order to avoid systematic uncertainties in the metallicity estimate we adopted the reddenings given in the Catalog of Classical Cepheids (Fernie et al. 1995) and removed the objects that are members of binary systems (Szabados 2003). We ended up with a sample of 151 Cepheids for which we searched in the literature for iron measurements based on high resolution spectra. We found accurate iron abundances for 48 Cepheids (Andrievsky et al. 2002a,b,c; Andrievsky et al. 2004; Luck et at. 2006; Mottini et al. 2006; Lemasle et at. 2007). Fortunately enough, the calibrating Cepheids cover a broad range in metallicity, namely -0.5 ≤[Fe/H]≤0.5.

2.1. Interstellar reddening correction

Before any physical information can be derived from photometric data, all colors and magnitudes have to be corrected for interstellar reddening. In order to constrain the absorption coefficients detailed observations of a sizable sample of standard stars in the southern hemisphere have been performed during three different periods (1960-61, 1970-71, 1980-81). There are very small differences between these three absolute calibrations of the Walraven system and transformations are very well studied. The zeropoint was set by the measurements of one B star passing through the zenith in South Africa (ω^1 Sco, spectral type B1.5V, $V_J = 3.96$ and $(B-V)_J = -0.04$, HD 144470). We underline that we used the data from South Africa (1970-71) transformed into the photometric system as valid for La Silla (1979-1991) and then we were able to apply the relations between Johnson and Walraven systems. On the basis of the quoted data the following relations were derived by Lub and Pel between magni-

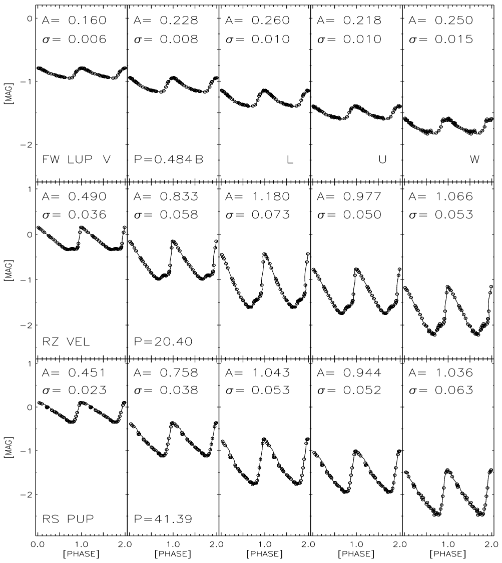

Fig. 1. From left to right light curves in the Walraven V, B, L, U, W bands for three Cepheids. From top to bottom short, intermediate, and long period Cepheids (see labeled values). For each band, the intrinsic scatter of the fit with a cubic spline and the amplitude are also plotted.

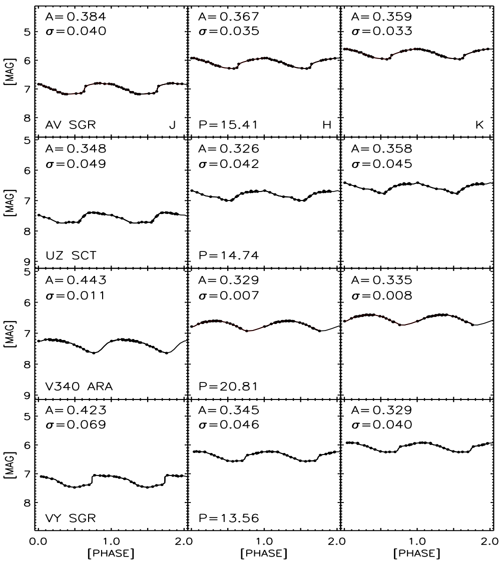

Fig. 2. From left to right J, H, K-band light curves for four Galactic Cepheids. The symbols are the same as in Fig. 1.

tudes, colors and color excesses in the Johnson and in the Walraven systems:

$$V_J = 6.886 - 2.5V - 0.082(V - B) \quad (1)$$

$$(B-V)_J = 2.57(V-B)-1.02(V-B)^2+0.05(V-B)^3 \quad (2)$$

$$E(B - V)_J/E(V - B) = 2.375 - 0.169(V - B) \quad (3)$$

$$A_{V_J}/E(B-V) = 3.17-0.16(V-B)-0.12E(V-B) \quad (4)$$

while the ratios between different color excess in the Walraven system are the following:

$$E(B - U)/E(V - B) = 0.61, \quad (5)$$

$$E(U - W)/E(V - B) = 0.45, \quad (6)$$

$$E(B - L)/E(V - B) = 0.39 \quad (7)$$

Thanks to the fact that the Walraven photometric system includes five bands, we can also define three reddening-free color indices. For a standard interstellar extinction law (Cardelli et al. 1989) they are the following:

$$[B - U] = (B - U) - 0.61(V - B) \quad (8)$$

$$[U - W] = (U - W) - 0.45(V - B) \quad (9)$$

$$[B - L] = (B - L) - 0.39(V - B) \quad (10)$$

It should be noted that, the Walraven system uses units of $\log_{10}(Intensity)$ instead of magnitudes ($-2.5\times\log_{10}(Intensity)$), therefore for transforming the distance moduli based on Johnson photometry we adopt $DM_W = -0.4 \times DM_J$.

2.2. Theory

In order to provide an independent calibration of the MIC relation we decided to use a homogeneous set of evolutionary models for intermediate-mass stars with scaled-solar chemical composition. The transformation into the observational plane was performed by adopting a set of atmosphere models with the same chemical composition (Castelli & Kuruck 2003). The reader interested in a detailed discussion concerning the input physics is referred to Pietrinferni et al. (2004). The adopted stellar masses range from $M = 3.5 - 10.0\ M_\odot$, while the metal and helium content are Z = 0.001, 0.002, 0.004, 0.008, 0.01, 0.0198, 0.03 and Y = 0.246, 0.248, 0.251, 0.256, 0.259, 0.273, 0.288. Fig. 3 shows the comparison between theory and observations for both the Johnson V_J, B_J-bands (top) and the Walraven V, B-bands (bottom). Individual distances were estimated using NIR mean magnitudes and the empirical NIR PL relations provided by Persson et al. (2004) and the reddening corrections provided by Fernie (1995). The dashed lines display the predicted first overtone blue edge (hotter) and the fundamental red edge (cooler) of the Cepheid instability strip (Bono et al. 2005).

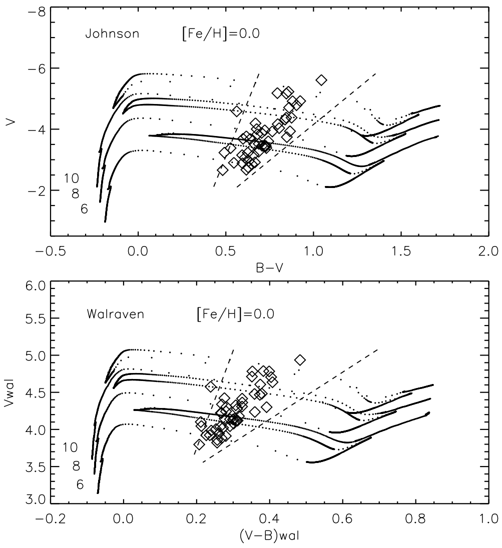

Fig. 3. Top: V_J,$B_J - V_J$ Johnson Color-Magnitude Diagram for calibrating Cepheids (diamonds). Solid lines display evolutionary tracks at solar chemical composition (Y=0.273, Z=0.0198) and different stellar masses (see labeled values). Individual distances for calibrating Cepheids were estimated using the NIR PL relations by Persson et al. (2004) and reddening estimates provided by Fernie (1995). The dashed lines show the edges of the instability strip. Bottom: same as the top, but for the Walraven V, B-bands.

3. Metallicity indices

In order to provide a new calibration of the MIC relation for Cepheids based on Walraven

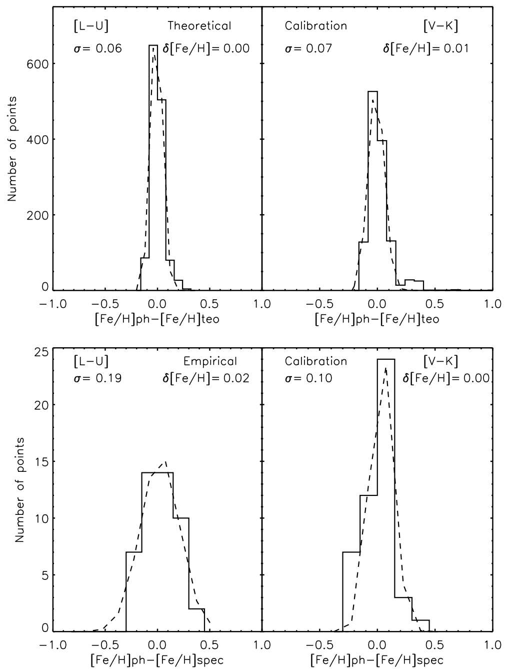

Fig. 4. Top: difference in iron abundance between theoretical MIC relations and spectroscopic abundances. The left panel refers to the MIC relation based on [L-U] color while the right one to the [V-K] color. Bottom: same as the top, but for the empirical MIC relations.

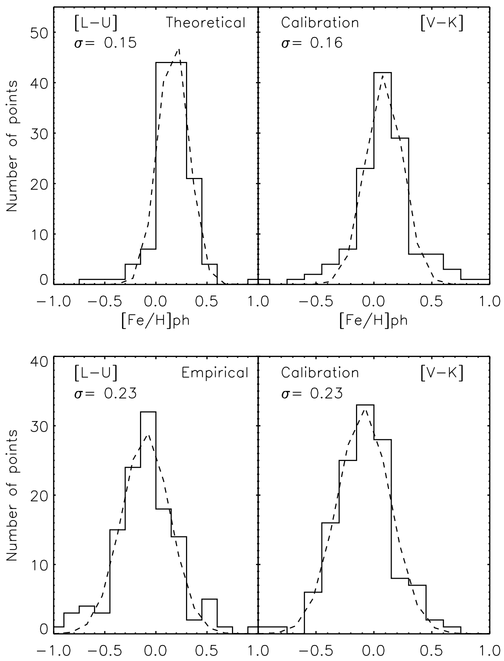

Fig. 5. Metallicity distribution of Galactic Cepheids based on theoretical (top panels), $\sim$ 150 objects, and empirical (bottom panels), $\sim$ 100 objects. The dashed lines show the Gaussian fits, the σ values are also labeled.

photometry we performed a multilinear regression fit between the observed (B-L) color, spectroscopic iron abundance and an independent color index (CI). In particular, we estimated the coefficients of the following MIC relation:

$$(B-L) = \alpha + \beta[Fe/H] + \gamma CI_0 + \delta[Fe/H]CI_0 \quad (11)$$

where the symbols have the usual meaning, and CI_0 indicates an unreddened color index. To estimate the theoretical MIC relations we selected, for each set of tracks at fixed metallicity (see §2.2), all the points located inside the predicted edges of the instability strip. Then we performed the multilinear regression fit (1) between the quoted metallicities and the predicted CIs.

We chose two different CIs for the multilinear regression, namely (L-U), as originally suggested by Pel & Lub (1978), and (V-K) since optical-NIR colors are good temperature indicators. Moreover (L-U) is also a gravity indicator and thus period dependent. By adopting these two colors we found that for the calibrating Cepheids the differences between photometric and spectroscopic abundances were $\delta[Fe/H]_{(L-U)} = 0.03$, $\sigma_{(L-U)} = 0.19$ and $\delta[Fe/H]_{(V-K)} < 0.01$, $\sigma_{(V-K)} = 0.11$. For theoretical calibration $\delta[Fe/H]_{(L-U)}$ <0.01, $\sigma_{(L-U)} = 0.08$ and $\delta[Fe/H]_{(V-K)}$ =0.01, $\sigma_{(V-K)} = 0.06$.

In order to constrain the possible occurrence of systematic errors introduced by reddening corrections we estimated a new set of MIC relations, but using reddening free color indices (see §2.1). These relations provide the following differences: empirical calibrations $\delta[Fe/H]_{[L-U]} = 0.02$, $\sigma_{[L-U]} = 0.19$ and $\delta[Fe/H]_{[V-K]} < 0.01$, $\sigma_{[V-K]} = 0.10$; theoretical calibrations $\delta[Fe/H]_{[L-U]}$ <0.01, $\sigma_{[L-U]}$ =

0.06 and $\delta[Fe/H]_{[V-K]}$ =0.01, $\sigma_{[V-K]} = 0.06$. We underline that these dispersions are mainly due to the standard deviation of the multilinear regression. In particular, we found $\sigma_{MIC([L-U])} = 0.001$ and $\sigma_{MIC([V-K])} = 0.006$ for theoretical relations and $\sigma_{MIC([L-U])} = 0.14$ and $\sigma_{MIC([V-K])} = 0.05$ for the empirical MICs. Fig. 4 shows the distribution of the difference between photometric estimates and spectroscopic iron measurements for theoretical (top panels) and empirical (bottom panels) MIC relations. Note that the left panels display the difference for the [L-U] colors while the right one for the $[V-K] = (V-K) - 2.9(B-V)$.

Finally, we applied the new reddening free empirical MIC relations to the non calibrating Cepheids ($\sim$ 100 objects) and estimated their individual iron abundances. The same outcome applies to the new reddening free theoretical MIC relations, but they have been applied to the entire sample of $\sim$ 150 Walraven Cepheids. Data plotted in Fig. 5 show that the metallicity distributions based on theoretical and empirical MIC relations based on different color indices do agree quite well. Moreover and even more importantly, the metallicity range covered by the photometric abundances is, within empirical and theoretical uncertainties, in good agreement with spectroscopic measurements (Andrievski et al. 2002; Yong et al. 2006; Lemasle et al. 2007)

4. Discussion

We provide new empirical and theoretical calibrations of the Walraven metallicity index. We ended up with two independent sets of MIC relations to estimate Cepheid iron abundances. The comparison between iron abundance estimates based on theoretical and empirical MIC relations brings forward two interesting findings: *i) Empirical Calibrations* – Cepheid iron abundances based on the empirical calibration agree quite well with spectroscopic measurements. The difference is on average 0.02 ± 0.02 dex with an intrinsic dispersion $\sigma \sim 0.2$ dex for the relation using the [L-U] reddening free color and 0.001 ± 0.002 dex with $\sigma \sim 0.10$ dex for the relation using the [V-K] reddening free color. *ii) Theoretical Calibration* – Iron abundances based on the theoretical MIC relations agree very well with spectroscopic measurements. The difference is on average < 0.001 dex with an intrinsic dispersion $\sigma = 0.06$ dex for the relation using the [L-U] reddening free color and 0.01 ± 0.02 dex with $\sigma = 0.07$ dex for the relation using the [V-K] reddening free color.

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