

# On the calibration of Red Giant Branch metallicity indicators in globular clusters: new relations based on an improved abundance scale

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**Abstract.** We present an improved calibration of photometric metallicity indicators, derived from the new metallicity scale for Globular Clusters presented by Carretta & Gratton (1997) and based on direct high resolution spectroscopy of 160 stars in 24 globular clusters.

We have carefully recalibrated the traditional abundance indices based upon the red giant branch (RGB) morphology, both in the  $V$ ,  $B - V$  and  $V$ ,  $V - I$  planes, namely the dereddened colour at the luminosity level of the horizontal branch (HB), and the magnitude difference between the HB and the RGB at a given dereddened colour.

Finally, we give new accurate relations to employ in the Simultaneous Metallicity Reddening method by Sarajedini (1994), also tied to the Carretta & Gratton (1997) abundance scale.

**Key words:** stars: abundances – globular clusters: general

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## 1. Introduction

Since globular clusters (GCs) are among the oldest objects in galaxies, they are widely recognized as very useful tracers of the chemical and dynamical evolution of their parent hosts.

The accurate knowledge of their global metal content, measured by the  $[\text{Fe}/\text{H}]$  ratio, is critical for many astrophysical problems. In particular, being very massive and luminous systems of coeval stars that show, to a first approximation, a similar (initial) chemical composition, globular clusters represent the cornerstones in establishing the existence of an age-metallicity relation and/or a metallicity-galactocentric distance gradient, up to the most distant regions of the galactic halo. This in turn provides strong constraints on models of galactic formation. Moreover, variations in the  $[\text{Fe}/\text{H}]$  content among globular clusters can be interpreted as a fossil record of the global processes of chemical enrichment occurred through the history of the Galaxy. Finally,

precise metallicities are one of the basic ingredients in deriving accurate ages using parallaxes measured by the Hipparcos astrometry satellite (see Gratton et al. 1997; Reid 1997).

Even if the best way to get a quantitatively accurate estimate of the metal abundance of any star is detailed abundance analysis of high resolution spectra, there are unfortunately some shortcomings that limit the application of this technique to the study of GCs. Due to their large distances, reliable high resolution, high signal-to-noise spectra can be obtained with the present day instrumentation only for the brightest giants. Only a handful of stars near the main sequence turn-off (hence reflecting the initial chemical composition, undisturbed by mixing in later evolutionary phases) have been observed yet. Moreover, high-resolution spectroscopy is a very time consuming observing technique.

Therefore, in the past years, a number of indirect metallicity indicators have been devised to overcome these problems. Almost all of them are based on integrated parameters that bypass the distance limit also for very far clusters, but they require a very accurate calibration in order to provide the true content in  $[\text{Fe}/\text{H}]$ . A direct calibration, able to tie the observed photometric indices to the actual number of iron atoms as measured from high resolution spectral line profiles is henceforth strongly needed. In Sect. 2 we discuss the philosophy of our approach; Sects. 3 and 4 are devoted to the presentation and discussion of new calibrations for several metallicity indicators; a short summary is presented in Sect. 5.

## 2. The reference metallicity scale

Traditionally, all indices have been tied up to now to the metallicity scale defined by the Zinn's group (Zinn & West 1984, Armandroff et al. 1992, Da Costa & Armandroff 1990; hereinafter ZW on the whole), systematically ignoring any later result from high dispersion spectroscopy. ZW's scale is a compilation of metallicities from several different parameters, all referred to the integrated parameter  $Q_{39}$ , and tied to a high resolution spectroscopic scale based on old photographic echelle spectra (see Zinn & West 1984). Moreover, there have been in the past years

**Table 1.** GCs used as calibrators. Data are taken from GC97, ZW, SL (Table 5), Sarajedini (1994, Table 1), and Sarajedini & Milone (1995, for NGC5053 and NGC4590). Y or N indicate in columns 3 and 9 whether the GC is a primary calibrator for GC97 and SL respectively.

GC	[Fe/H] CG97	Direct spectr.?	[Fe/H] ZW	E(B-V)	(B-V) <sub>0,g</sub>	$\Delta V_{1,2}$ <i>V, B - V</i>	$\Delta V_{1,1}$ <i>V, B - V</i>	calib. in SL?	(V-I) <sub>0,g</sub>	$\Delta V_{1,2}$ <i>V, V - I</i>
NGC104 (47Tuc)	-0.70	Y	-0.71	0.04	0.958	1.275	0.798	Y	1.032	1.028
NGC288	-1.07	Y	-1.40	0.02	0.852	1.884	1.503	N		
NGC362	-1.15	Y	-1.28	0.03	0.832	2.050	1.741	N		
NGC1261	-1.09	N	-1.31	0.00	0.860	2.095	1.735	N		
NGC1851	-1.08	N	-1.29	0.02	0.873	1.806	1.433	Y	0.953	1.609
NGC1904	-1.37	Y	-1.69	0.01	0.801	2.332	2.001	N		
NGC4590 (M68)	-1.99	Y	-2.09	0.07	0.694	2.810	2.508	Y	0.885	2.470
NGC5053	-2.43	N	-2.41	0.06	0.647	3.101	2.741	Y	0.847	2.770
NGC6352	-0.64	Y	-0.60	0.21	0.994	0.953	0.591	N		
NGC6397	-1.82	Y	-1.91	0.18	0.717	2.842	2.483	N	0.904	2.330
NGC6535	-1.53	N	-1.75	0.44	0.745	2.537	2.134	N		
NGC6752	-1.42	Y	-1.54	0.04	0.781	2.264	1.873	Y	0.949	1.935
NGC7078 (M15)	-2.12	Y	-2.17	0.10	0.691	2.972	2.601	Y	0.882	2.538
NGC7089 (M2)	-1.34	N	-1.58						0.934	2.039
Eridanus	-1.18	N	-1.41	0.03	0.838	1.897	1.596	N		
ESO121	-0.83	N	-0.93	0.03	0.907	1.507	1.101	N		
Lindsay1	-0.94	N	-1.10	0.04	0.864	1.888	1.522	N		
Pal14	-1.36	N	-1.60	0.05	0.803	2.288	1.939	N		

several claims (e.g. Manduca 1983; Frogel et al. 1983) that the integrated light measurements, upon which the ZW scale was primarily based, are likely to underestimate the true metallicities of clusters with exceptionally blue horizontal branches (HBs), since the HB morphology affects the determination of the  $Q_{39}$  index.

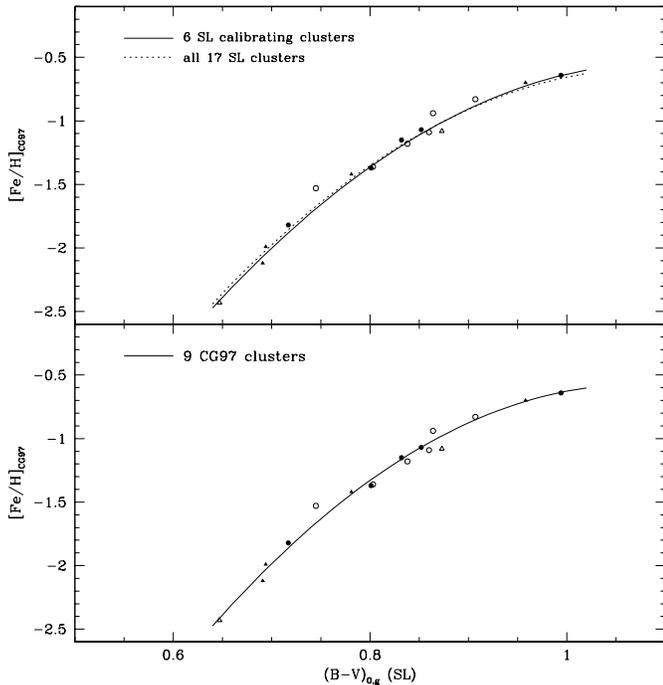
Very recently, Carretta & Gratton (1997; CG97) used high dispersion, high signal-to-noise spectra of more than 160 red giants in 24 clusters to derive a new metallicity scale based on direct detailed abundance analysis, coupled with the most recent and upgraded model atmospheres (Kurucz 1992). The observational material consisted in equivalent widths (EWs) measured on high quality CCD echelle spectra. Different sets of EWs taken from literature were carefully checked and, if necessary, brought on a common, homogeneous system, tied to EWs from the highest resolution spectra. The same set of atomic line parameter was used for all stars, with model atmospheres from the Kurucz grid. Also the reference value for the solar [Fe/H] was obtained from the same set of atomic parameter and the solar model extracted from the same grid used for giant stars. Input atmospheric parameters (effective temperature and gravity) for all stars were obtained from the Frogel et al. papers (e.g. Frogel et al. 1983, but see detailed references in CG97), mostly based on accurate infrared colours and magnitudes. The choice of a temperature scale has an impact on the derived metallicities: CG97 estimate that the adopted one cannot be systematically incorrect by more than about 50 K, given the small differences found in abundances derived from FeI and FeII. They also estimate that

random errors, due to uncertainties in individual star colours and cluster reddenings, are of the same order of magnitude.

The average internal uncertainty in metal abundance on the CG97 scale is 0.06 dex, resulting in a precise ranking of cluster metallicities. CG97 also demonstrated that ZW's scale is clearly non-linear, in comparison to their improved scale. All [Fe/H] values on the ZW's scale were then translated to the CG97 scale by means of a quadratic interpolating relation, covering the range in [Fe/H] spanned by the 24 calibrating clusters ( $-2.5 \lesssim [\text{Fe}/\text{H}] \lesssim -0.5$ ).

In the present paper we recalibrate some of the most used metal abundance indicators to the new CG97 scale, concentrating on those based on the morphology and position of the red giant branch (RGB) in the colour-magnitude diagram (CMD). We will present calibrations for the indices  $(B - V)_{0,g}$ ,  $\Delta V_{1,2}$ ,  $\Delta V_{1,1}$  in the  $V, B - V$  plane, and the analogous in the  $V, V - I$  one, as defined in Sect. 3.

Such a revised calibration is needed, since the advent of sophisticated high resolution imaging facilities outside the atmosphere, like the *Hubble Space Telescope*, allows the observations of clusters in the whole Galaxy, providing CMDs with giant branches well defined also for very distant or obscured objects. Precise photometry of extragalactic clusters (in M31, in the Magellanic Clouds and in Fornax) is also feasible (see e.g. Fusi Pecci et al. 1996), and it is possible to derive for them quite accurate metallicities, provided that a good calibration from nearby clusters is available.



**Fig. 1.** Calibration of the  $(B - V)_{0,g}$  parameter using the CG97 metallicity scale and the cluster sample by SL. The upper panel shows the calibrations obtained using only the 6 SL primary calibrators (solid line) and all the 17 clusters (dotted line). In the lower panel the calibration is based only upon the 9 clusters that have metallicities derived by CG97 from direct analysis (CG97 reference clusters). In both panels filled symbols represent clusters with  $[\text{Fe}/\text{H}]$ 's derived in CG97, while open symbols represent clusters with ZW metallicities corrected to the CG97 scale. Triangles, filled or open, indicate the 6 SL primary calibrators.

### 3. Photometric metallicity indicators in the $V, B - V$ plane

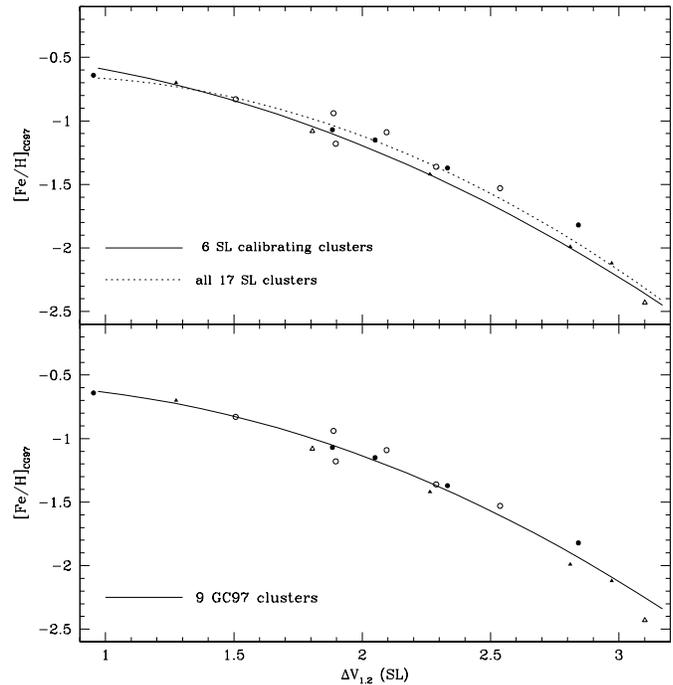
The position and morphology of the RGB in the  $V, B - V$  plane are theoretically well tied to the metal content of the stars in a cluster: the higher the metal content, the cooler the effective temperature  $T_{eff}$  and the redder the RGB stars.

In principle, for every GC with a good CMD of the brightest evolutionary phases, metallicity indicators may be derived from its RGB. However, to obtain a reliable calibration, homogeneous measurements are needed. We will then select data sets homogeneous enough to match the quality of the calibrating metallicity scale.

#### 3.1. The $(B - V)_{0,g}$ index

The index  $(B - V)_{0,g}$  (Sandage & Smith 1966) is the de-reddened colour of the RGB at the luminosity level of the HB in the  $V, B - V$  CMD.

As one of the most homogeneous available samples, we adopted the one published by Sarajedini and Layden (1997, SL). Their study extended to the  $V, B - V$  plane the Simultaneous Metallicity Reddening method by Sarajedini (1994). They selected high quality CCD photometric studies of 17 globular



**Fig. 2.** Calibration of the  $\Delta V_{1,2}$  parameter of SL using the CG97 metallicities. The meaning of symbols is as in Fig. 1.

clusters (15 galactic and 2 Magellanic Clouds clusters), 6 of which were used as primary calibrators. De-reddened colours are adopted from their Table 5.

Whenever possible, we try to rest our calibration on the GCs directly analyzed in CG97. Among the 17 SL clusters, only 9 have  $[\text{Fe}/\text{H}]$  values from direct high-resolution spectroscopy; for all other cases, we translated the older ZW value to the new scale with eq. 7 in CG97. The range in metallicity covered by CG97 is  $-2.5 \lesssim [\text{Fe}/\text{H}] \lesssim -0.5$ , so all relations here derived are strictly valid only in this interval. We did not try to extend their validity to higher metallicities, e.g. by applying a constant offset given by the difference between ZW and CG97 values at  $[\text{Fe}/\text{H}] = -0.54$  (the most metal-rich clusters in common): there is in fact the possibility that the strong Ca lines, upon which ZW determinations are based, saturate at very high metallicities.

SL used the old ZW scale (ZW; Da Costa & Armandroff 1990; Armandroff et al. 1992). To derive the two expressions for  $[\text{Fe}/\text{H}]$ , as a function i) of  $(B - V)_{0,g}$  and ii) of  $\Delta V_{1,2}$  needed to simultaneously solve for metallicity and reddening, they fitted the data using linear regressions. Note however that in previous studies (like Costar & Smith 1988) the linearity of the  $(B - V)_{0,g}$  calibration at the low and high metallicity ends was questioned. We have repeated the calibration, but in terms of  $[\text{Fe}/\text{H}]_{CG97}$ , and results are shown in Fig. 1. Adopting the CG97 scale, this non-linear effect is obviously enhanced, and it is possible to see also by eye that a linear fit is a poor approximation.

The resulting best-fit quadratic relations connecting  $(B - V)_{0,g}$  and  $[\text{Fe}/\text{H}]_{CG97}$  shown in Fig. 1, upper panel, are:

$$[\text{Fe}/\text{H}] = 20.103(B - V)_{0,g} - 9.141(B - V)_{0,g}^2 - 11.595 \quad (1)$$

when using only the 6 SL primary calibrating clusters (with *r.m.s.* deviation  $\sigma = 0.067$ , and correlation coefficient  $r = 0.997$ ) and

$$[\text{Fe}/\text{H}] = 20.129(B - V)_{0,g} - 9.253(B - V)_{0,g}^2 - 11.532 \quad (2)$$

when using all the 17 SL clusters ( $\sigma = 0.059$ ,  $r = 0.994$ ). Error bars in  $[\text{Fe}/\text{H}]$  can be derived from the CG97 paper: they range from 0.01 to 0.11 dex, with an average value of 0.06 dex. SL apparently did not quote any error associated to their  $(B - V)_{0,g}$  values.

To corroborate the visual impression of non linearity, we tested the statistical significance of the terms of higher order in Eqs. 1 and 2 by a *t*-test.

The lower panel of Fig. 1 displays instead the calibration based only upon the 9 CG97 reference clusters; the corresponding relation is:

$$[\text{Fe}/\text{H}] = 21.790(B - V)_{0,g} - 10.155(B - V)_{0,g}^2 - 12.262 \quad (3)$$

( $\sigma = 0.041$  and  $r = 0.998$ ). In our view, Eq. 3 is the best interpolating fit, since it has the lower formal statistical *r.m.s.* and higher correlation coefficient. Note however that differences in the derived  $[\text{Fe}/\text{H}]$  values from the one obtained from Eqs. 1 and 2 look negligible (0.01 to 0.02 dex on average, on a range of 0.35 mag in colour).

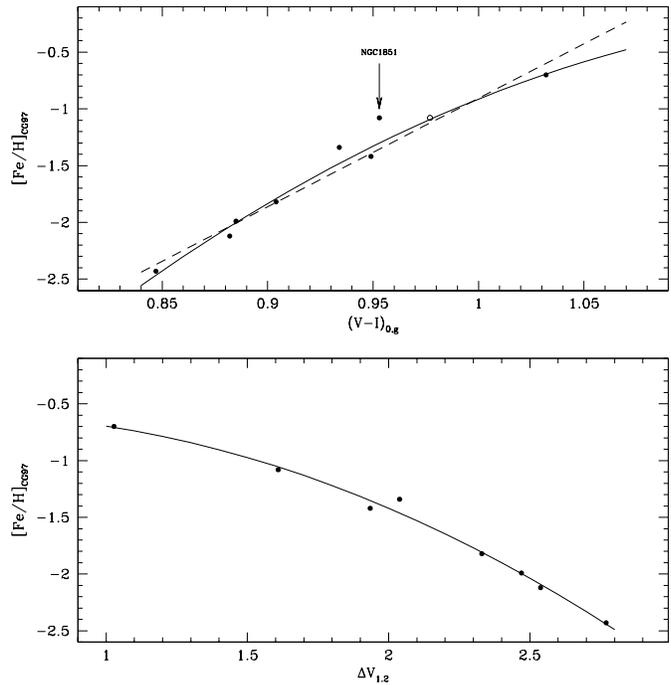
As a check for the validity of the relations found, we used  $(B - V)_{0,g}$  values from two recent high quality photometric studies, namely M3 ( $(B - V)_{0,g} = 0.80$ ; Ferraro et al. 1997) and M5 ( $(B - V)_{0,g} = 0.83$ ; Sandquist et al. 1996), which are not among the clusters used to derive the calibrations. Using Eq. 3 we obtain  $[\text{Fe}/\text{H}] = -1.33$  for M3, and  $[\text{Fe}/\text{H}] = -1.17$  for M5. These values have to be compared with  $-1.34 \pm 0.06$  (M3) and  $-1.11 \pm 0.11$  (M5) obtained from direct analysis by CG97.

This test suggests that with the present calibration we are able to establish a very good ranking in cluster metallicities, quite comparable with that given by the CG97 scale. Eq. 3 comes out as best calibration of the  $(B - V)_{0,g}$  parameter as metallicity indicator, and can be adopted as one of the basic equations of the Simultaneous Metallicity Reddening method (SMR, Sarajedini 1994).

### 3.2. The $\Delta V_{1,2}$ and $\Delta V_{1,1}$ parameters

The second index we recalibrated is a variation of the classical  $\Delta V_{1,4}$  parameter, that measures the difference in *V* magnitude between the HB and the level of the RGB at the de-reddened colour  $(B - V)_0 = 1.4$  (Sandage & Wallerstein 1960). For consistency, we used again the data set from SL, that measured instead the indices  $\Delta V_{1,2}$  and  $\Delta V_{1,1}$ , referred to the de-reddened colours  $(B - V)_0 = 1.2$  and  $(B - V)_0 = 1.1$ , respectively. As stated by SL, choosing bluer reference colours could be useful in the case of RGBs poorly populated in their upper parts.

These parameters, taken as before from SL Table 5, have been calibrated (see Eqs. 4 and 5), and the case of  $\Delta V_{1,2}$  is presented in Fig. 2 ( $\Delta V_{1,1}$  has a very similar behaviour and is not shown).



**Fig. 3.** Calibration of the  $(V - I)_{0,g}$  (upper panel) and  $\Delta V_{1,2}$  (lower panel) parameters in the  $V, V - I$  plane using the new CG97 metallicities. The solid lines in the both panels represent a quadratic interpolation through the data; the dashed line is the linear best fit. In the upper panel the open symbol represents NGC1851 once "corrected" as explained in the text.

At odds with the case of  $(B - V)_{0,g}$ , there seems to be a clear difference between the calibrations based on the 6 SL primary calibrating clusters and on the whole SL sample. In particular, for a given  $\Delta V_{1,2}$  the first relation gives a lower value of  $[\text{Fe}/\text{H}]$ , and the effect seems to be stronger at low/intermediate metallicity, while at higher metallicities the two lines intersect. In fact, using the relation derived from the 6 SL calibrators  $[\text{Fe}/\text{H}]$  values are underestimated on average by 0.08 dex in the interval  $-1.9 \lesssim [\text{Fe}/\text{H}] \lesssim -1.0$ , with respect to the other calibration.

We have no explanation for this feature; here we only want to note that SL stated that "*These secondary calibrators have not been used in the determination of the (omissis) fitted relations. They only serve to corroborate these relations*". It is difficult to see from their Fig. 8 if also with ZW metallicities their primary calibrating clusters provide an underestimation of  $[\text{Fe}/\text{H}]$ . It is however interesting to note that the application of the SMR method in the  $V, B - V$  plane resulted in lower derived abundances with respect to spectroscopic determinations (based e.g. on the CaII triplet).

Finally, we re-calibrated the  $\Delta V_{1,2}$  - metallicity relation using the 9 CG97 primary calibrating clusters. The relation is shown in the lower panel of Fig. 2 and is given by:

$$[\text{Fe}/\text{H}] = 0.236\Delta V_{1,2} - 0.245\Delta V_{1,2}^2 - 0.627 \quad (4)$$

( $\sigma = 0.072$ ,  $r = 0.993$ ). This calibration provides  $[\text{Fe}/\text{H}]$  values agreeing very well with those obtained from all the 17 clusters of SL, and clearly represent a good fit to all the data.

The case for the  $\Delta V_{1,1}$  index closely reproduces that of  $\Delta V_{1,2}$ ; the resulting calibration based on the 9 CG97 clusters is:

$$[\text{Fe}/\text{H}] = 0.089\Delta V_{1,1} - 0.248\Delta V_{1,1}^2 - 0.612 \quad (5)$$

( $\sigma = 0.075$ ,  $r = 0.992$ ).

In conclusion, these new calibrations are able to provide metal abundance with a *r.m.s.* dispersion of about  $0.04 \lesssim r.m.s. \lesssim 0.07$  dex, comparable to the errors usually obtained from direct, high resolution spectroscopy of stars in GCs.

Eqs. 3 and 4 (or 3 and 5) can be used in the application of the SMR method in the  $V, B - V$  plane.

#### 4. Re-calibration of the SMR method in the $V, V-I$ plane

The SMR method was originally devised by Sarajedini (1994) in the  $V, V - I$  plane. His calibration was based on the ZW scale and high precision CCD photometry obtained by Da Costa & Armandoff (1990).

For the present analysis we used values for 6 clusters as in Table 1 of Sarajedini (1994), integrated by values for NGC 5053 (Sarajedini & Milone 1995) and M 68 (from photometry of Walker 1994, as quoted in Sarajedini & Milone 1995) in order to extend the method to very low metallicity clusters. Data are shown in Table 1. The parameter definition is analogous to that in the  $V, B - V$  plane: we want  $[\text{Fe}/\text{H}]$  as a function both of  $(V - I)_{0,g}$  and of  $\Delta V_{1,2}$ .

Due to the small sample, all clusters were used to obtain the new calibrations. Original values from direct analysis by CG97 were used whenever possible; for the 3 remaining GCs, we transformed ZW values to the CG97 scale.

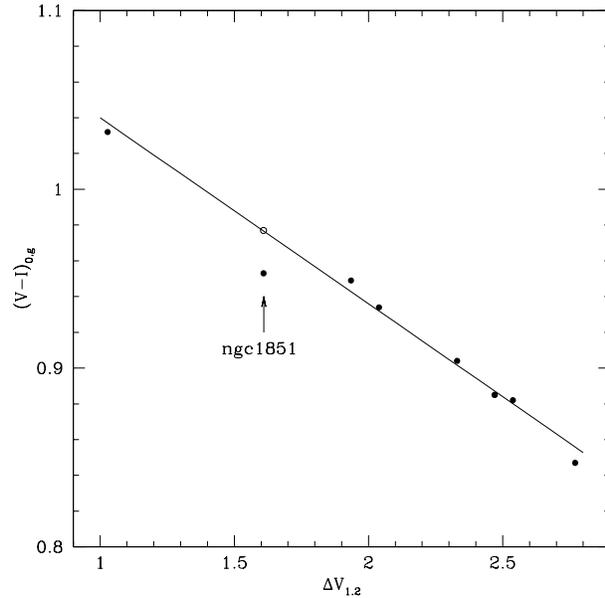
Fig. 3 shows the resulting calibrations (and also a potential problem for the  $(V - I)_{0,g}$  index). The relation obtained using the 8 clusters for  $\Delta V_{1,2}$  is well fitted with a quadratic polynomial (Fig. 3, lower panel), like for the  $V, B - V$  plane, and is given by:

$$[\text{Fe}/\text{H}] = 0.304\Delta V_{1,2} - 0.342\Delta V_{1,2}^2 - 0.659 \quad (6)$$

( $\sigma = 0.064$ ,  $r = 0.996$ ). The quadratic term is found to be highly significant, with a confidence level of 99.5 %.

In the case of  $(V - I)_{0,g}$  instead, both a linear and a quadratic interpolation seem to fit equally well the data (see Fig. 3, upper panel). The statistical significance of the quadratic term is lower than in all previous cases, being only between 90 and 95 %. Circumstantial evidence in favour of a quadratic relation comes, in our view, from the fact that the relation between  $(V - I)_{0,g}$  and  $\Delta V_{1,2}$  seems to be a straight line (see Fig. 4), the only discrepant point being NGC1851, and the fact that  $\Delta V_{1,2}$  is quadratically related to  $[\text{Fe}/\text{H}]$ .

We have derived again the calibration for the  $(V - I)_{0,g}$  index in the supposition something is wrong with the  $(V - I)_{0,g}$  value for NGC1851. We have “corrected” it to the value it should



**Fig. 4.** Comparison of the  $(V - I)_{0,g}$  and  $\Delta V_{1,2}$  values used by Sarajedini (1994) and Sarajedini and Milone (1995) to calibrate the SMR method in the  $V, V - I$  plane. The open symbol represents the value of  $(V - I)_{0,g}$  for NGC1851, “corrected” as explained in the text.

have if it followed the fit in Fig. 4 (a correction of 0.024 mag, rather large given the errors quoted by Da Costa & Armandoff 1990). The statistical significance of the quadratic term remains virtually unchanged even if, of course, the *r.m.s.* dispersion of the quadratic interpolation decreases (from 0.12 to 0.08 dex).

As a further test, we used the value  $(V - I)_{0,g} = 0.951$  (Ferraro et al. 1997) for M3, and obtained  $[\text{Fe}/\text{H}] = -1.27$  and  $-1.34$  using the quadratic and linear interpolations with the original  $(V - I)_{0,g}$  value for NGC1851, respectively; and  $-1.32$  and  $-1.37$  using the equivalent relations where the  $(V - I)_{0,g}$  has been corrected as described. These values, while nicely bracketing the spectroscopic value  $[\text{Fe}/\text{H}] = -1.34 \pm 0.02$  (CG97), do not tell anything definitive about the true form of the calibration at the high metallicity end.

In view of this, we give both the linear and quadratic expressions for the  $(V - I)_{0,g} - [\text{Fe}/\text{H}]$  relation (with the modified  $(V - I)_{0,g}$  value for NGC1851):

$$[\text{Fe}/\text{H}] = 9.586(V - I)_{0,g} - 10.491 \quad (7)$$

$$[\text{Fe}/\text{H}] = 42.981(V - I)_{0,g} - 17.772(V - I)_{0,g}^2 - 26.122 \quad (8)$$

We however think it safer to apply the SMR method in the  $V, B - V$  plane, at least until more homogeneous values for  $(V - I)_{0,g}$  are supplied.

Moreover, note that while the  $\Delta V_{1,2}$  values in the  $V, V - I$  and  $V, B - V$  planes are linearly correlated, the run of  $(V - I)_{0,g}$  against  $(B - V)_{0,g}$  is not so clear, especially at the high metallicity end. Uncertainties in the transformation between the absorption coefficients in different bands, random errors in the adopted reddening, the adoption of different standard system for the  $I$

magnitudes could all be possible sources for the observed disagreement, that seems to affect the  $(V - I)_{0,g}$ , but much less a differential measure as the  $\Delta V_{1,2}$ .

## 5. Summary

We used the new and homogeneous metallicity scale, derived by CG97 from updated model atmospheres and direct detailed abundance analysis of high resolution spectra of globular cluster giants, to calibrate the traditional RGB photometric indicators in terms of the [Fe/H] ratio.

Especially in the  $V, B - V$  plane, the relations found provide very good relative determinations of [Fe/H] with an uncertainty on a single measurement of 0.08 dex on average, and as low as 0.04 dex. This goes towards lessening the disagreement existing in the past between photometric and spectroscopic determination of the metal abundance in globular clusters.

*Acknowledgements.* EC wishes to dedicate this work to the memory of his beloved grandmother, Maria Donata.

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