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# Bolometric correction and spectral energy distribution of cool stars in Galactic clusters<sup>★</sup>

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## ABSTRACT

We have investigated the relevant trend of the bolometric correction (BC) at the cool-temperature regime of red giant stars and its possible dependence on stellar metallicity. Our analysis relies on a wide sample of optical–infrared spectroscopic observations, along the  $3500 \text{ Å} \Rightarrow 2.5 \text{ μm}$  wavelength range, for a grid of 92 red giant stars in five (three globular + two open) Galactic clusters, along the full metallicity range covered by the bulk of the stars,  $-2.2 \leq [\text{Fe}/\text{H}] \leq +0.4$ .

Synthetic  $BVR_CI_C JHK$  photometry from the derived spectral energy distributions allowed us to obtain robust temperature ( $T_{\text{eff}}$ ) estimates for each star, within  $\pm 100 \text{ K}$  or less. According to the appropriate temperature estimate, blackbody extrapolation of the observed spectral energy distribution allowed us to assess the unsampled flux beyond the wavelength limits of our survey. For the bulk of our red giants, this fraction amounted to 15 per cent of the total bolometric luminosity, a figure that raises up to 30 per cent for the coolest targets ( $T_{\text{eff}} \lesssim 3500 \text{ K}$ ). Overall, we obtain stellar  $M_{\text{bol}}$  values with an internal accuracy of a few percentages. Even neglecting any correction for lost luminosity etc., we would be overestimating  $M_{\text{bol}}$  by  $\lesssim 0.3 \text{ mag}$ , in the worst cases. Making use of our new data base, we provide a set of fitting functions for the  $V$  and  $K$  BC versus  $T_{\text{eff}}$  and versus  $(B - V)$  and  $(V - K)$  broadband colours, valid over the interval  $3300 \leq T_{\text{eff}} \leq 5000 \text{ K}$ , especially suited for red giants.

The analysis of the  $BC_V$  and  $BC_K$  estimates along the wide range of metallicity spanned by our stellar sample shows no evident drift with  $[\text{Fe}/\text{H}]$ . Things may be different for the  $B$ -band correction, where the blanketing effects are more and more severe. A drift of  $\Delta(B - V)$  versus  $[\text{Fe}/\text{H}]$  is in fact clearly evident from our data, with metal-poor stars displaying a ‘bluer’  $(B - V)$  with respect to the metal-rich sample, for fixed  $T_{\text{eff}}$ .

Our empirical bolometric corrections are in good overall agreement with most of the existing theoretical and observational determinations, supporting the conclusion that (a)  $BC_K$  from the most recent studies are reliable within  $\lesssim \pm 0.1$  over the whole colour/temperature range considered in this paper, and (b) the same conclusion apply to  $BC_V$  only for stars warmer than  $\simeq 3800 \text{ K}$ . At cooler temperatures the agreement is less general, and MARCS models are the only ones providing a satisfactory match to observations, in particular in the  $BC_V$  versus  $(B - V)$  plane.

**Key words:** stars: atmospheres – stars: late-type – globular clusters: general – Galaxy: stellar content – infrared: stars.

## 1 INTRODUCTION

A physical assessment of the bolometric emission of stars is a mandatory step for any attempt to self-consistently link observa-

tions and theoretical predictions of stellar evolution. The importance of this comparison actually reverberates into a wide range of primary astrophysical questions, ranging from the validation of the reference input physics for nuclear reactions in the stellar interiors to the study of integrated spectrophotometric properties of distant galaxies, through stellar population synthesis models.

By definition, the effective temperature ( $T_{\text{eff}}$ ) and physical size ( $R$ ) of a star provide the natural constraint to its emerging flux, as  $L \propto R^2 T_{\text{eff}}^4$ . If  $L$  is a known property for a star, then we could physically

<sup>★</sup>Based on observations made at La Palma, at the Spanish Observatorio del Roque de los Muchachos of the IAC, with the Italian Telescopio Nazionale Galileo (TNG) operated by the Fundación Galileo Galilei of INAF.

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‘rescale’ the spectral energy distribution (SED), and infer, from the observed flux, the distance of the body,  $d$ , or its absolute size ( $R$ ), through a measure of the apparent angular extension,  $\theta = (R/d)^2 \propto L T_{\text{eff}}^{-4} d^{-2}$  (Ridgway et al. 1980; Dyck et al. 1996; Perrin et al. 1998; Richichi et al. 1998).

As is well known, however,  $L$  cannot, in principle, be measured *directly*, a task for which an ideal detector that is equally sensitive to the whole spectral range is required. The lack of this crucial piece of information is often palliated by indirect observing methods, trying to pick up the bulk of stellar emission through broad-band photometry within the appropriate spectral range according to target temperature.<sup>1</sup> Relying on this approach, Johnson (1966) derived the bolometric versus temperature scale for red giant stars, while Code et al. (1976) explored the same relation for hot early-type stars, through satellite-borne ultraviolet (UV) observations. As an alternative way, many authors tried a fully theoretical assessment of the problem, by studying the  $f_{\text{bol}}$  versus  $f_{\lambda}$  relationship on the basis of model grids of stellar atmospheres and thus replacing observations with synthetic photometry directly computed on the theoretical SED (Bessell, Castelli & Plez 1998; Bertone et al. 2004).

Rather than focussing on luminosity, Wesselink (1969) originally proposed a further application of this method, just looking at the bolometric surface brightness, namely  $\mu = f_{\text{bol}}/\theta^2$ , to lead to a refined temperature scale of stars in force of the fundamental relationship  $\mu = \sigma T_{\text{eff}}^{-4}$  ( $\sigma$  being the Stefan–Boltzmann constant). The so-called surface-brightness technique, then better recognized as the IR-flux method (IRFM), has been applied extensively to the study of red giant and supergiant stars (Blackwell, Shallis & Selby 1979; di Benedetto & Rabbia 1987; Blackwell & Lynas-Gray 1994; Alonso, Arribas & Martínez-Roger 1999; Ramírez & Meléndez 2005; González Hernández & Bonifacio 2009), taking advantage of its distance-independent results, providing to match the angular measure of stellar radii with the estimate of the bolometric flux from infrared observations, i.e.  $\mu = (f_{\text{bol}}/f_{\text{IR}}) f_{\text{IR}}$ .

Although in different forms, all the previous methods used theoretical models of stellar atmospheres to derive the appropriate ‘correcting factor’  $\mathcal{R} = f_{\text{bol}}/f(\lambda)$  and convert observed or synthetic monochromatic magnitudes  $m(\lambda)$  to the bolometric scale.<sup>2</sup>

Taking the Sun as a reference source for our calibration, we could write more explicitly:

$$[m_{\text{bol}} - m(\lambda)] - [m_{\text{bol}} - m(\lambda)]_{\odot} = -2.5 \log(\mathcal{R}/\mathcal{R}_{\odot}). \quad (1)$$

Equation (1) actually leads to the straight definition of bolometric correction,  $\text{BC}(\lambda)$ , namely

$$\text{BC}(\lambda) = [m_{\text{bol}} - m(\lambda)] = -2.5 \log \mathcal{R} + \text{BC}(\lambda)_{\odot}. \quad (2)$$

Aside from the historical definition, that originally considered BC only to photographic ( $m_{\text{pg}}$ ) or visual ( $m_{\text{V}}$ ) magnitudes (Kuiper 1938), one can nowadays easily extend the definition to any waveband. A careful analysis of equation (2) makes clear some important properties of BC: (i) the value of  $\mathcal{R}$  is a composite function of stellar fundamental parameters, namely  $\mathcal{R} = \mathcal{R}(T_{\text{eff}}, \log g, [X/H])$  so that, for fixed effective temperature, BC may display some dependence on stellar gravity ( $g$ ) and chemical composition ( $[X/H]$ ). (ii)

The value of  $\mathcal{R}$  (and, accordingly, of BC) is minimum when our observations catch the bulk of stellar luminosity. For this reason, high values of  $\text{BC}_{\text{V}}$  must be expected when observing for instance cool giant stars in the V band, or hot O-B stars in the infrared K band. (iii) The definition of the BC scale strictly depends on the assumed reference value for the Sun, which therefore must univocally fix the ‘zero-point’ of the scale (Bessell et al. 1998).

In this framework, we want to tackle here the central question of the possible BC dependence on stellar metallicity. This effect could be of special importance, in fact, in order to more confidently set the bolometric versus temperature scale for cool red giants, where the intervening absorption of diatomic (TiO *in primis*) and triatomic ( $\text{H}_2\text{O}$ ) molecules heavily modulate the stellar SED with sizeable effects on optical and NIR magnitudes (e.g. Gratton et al. 1982; Bertone et al. 2008). As a matter of fact, still nowadays the many efforts devoted to the definition of the BC versus  $\log T_{\text{eff}}$  relationship led to non-univocal conclusions, with large discrepancies among the different sources in the literature as far as stars of K spectral type or later are concerned (Flower 1975, 1977; Bessell & Wood 1984; Houdashelt, Bell & Sweigart 2000; Bertone et al. 2004; Worthey & Lee 2006).

This issue actually has an even more important impact on the study of the integrated spectrophotometric properties of resolved and unresolved stellar systems, as red giants and other post-main-sequence (PMS) stars provide a prevailing fraction (2/3 or more; Buzzoni 1989) of the total luminosity of the population. A fair definition of the BC scale becomes, therefore, of paramount importance to self-consistently convert theoretical H–R and observed c–m diagrams of a stellar population (Flower 1996; VandenBerg & Clem 2003) and to more confidently assess the physical contribution of the different stellar classes.

A study of the BC dependence on metal abundance has been previously attempted by many authors mainly relying on a fully theoretical point of view to exploit the obvious advantage of stellar models to account, in a controlled way, for a global or selective change of metal abundance. In this regard, Tripicco & Bell (1995) and Cassisi et al. (2004), among others, tried to explore the effect of  $\alpha$  elements enhancement (namely O, Mg, Ca, Ti etc.) in stellar SED, while Girardi et al. (2007) focused on the possible impact of helium abundance on BC. As a major drawback of these efforts, however, one has to report the admitted limitation of model atmospheres to accurately describe the spectrophotometric properties of K- and M-type stars, that are cooler than 4000 K (see Bertone et al. 2008, on this important point).

On the other hand, a fully empirical approach has been devised by Montegriffo et al. (1998) and Alonso et al. (1999), among others, trying to reconstruct stellar SED, and there from infer the bolometric flux,  $f_{\text{bol}}$ , through optical broad-band photometry of stars in the Galactic field or in globular clusters. A recognized limitation of these studies is, however, that they may suffer from the lack of coverage of the stellar parameter space offered by the observations. Moreover, as far as the cool-star sequence is concerned, optical multicolour photometry, alone, partially misses the bulk of stellar emission (more centred towards the NIR spectral window); in addition, by converting broad-band magnitudes into monochromatic flux densities, the stellar SED is reconstructed at a very poor spectral resolution, thus possibly losing important features that may bias the inferred bolometric energy budget.

On this line, however, we want to further improve the analysis proposing here more complete spectroscopic observations for a large grid of red giant stars in several Galactic clusters along the entire metallicity scale from very metal-poor (i.e.  $[\text{Fe}/\text{H}] \simeq -2.2$  dex)

<sup>1</sup>Recalling that emission peak roughly obeys the Wien law, i.e.  $T\lambda_{\text{peak}} \simeq \text{const}$ .

<sup>2</sup>For a more detailed analysis, note that the ratio  $\mathcal{R}$  dimensionally matches the definition of ‘equivalent width’, and it gives a measure of how ‘broad’ is the whole SED compared to the monochromatic emission density at the reference  $\lambda$ .

to supersolar ( $[\text{Fe}/\text{H}] \simeq +0.4$  dex) stellar populations. Our observations span the whole optical and NIR wavelength range, thus allowing a quite accurate shaping of stellar SED. As we will demonstrate in the following discussion, our procedure allowed us to sample about 70–90 per cent of the total emission of our sample stars, thus leading to a virtually *direct* measure of  $f_{\text{bol}}$ , even for M-type stars as cool as 3500 K.

We will arrange our discussion by presenting, in Section 2, our stellar data base together with further available information in the literature. The analysis of the observing material will be assessed in more detail in Section 3, while in Section 4 we will derive the SED for the whole sample leading to an estimate of the effective temperature and bolometric correction for each star. The discussion of the inferred BC–colour–temperature scale will be the focus of Section 5, especially addressing the possible dependence of BC on stellar metallicity. A comparison of our results with other relevant BC calibration in the literature will also be carried out in this section, while in Section 6 we will present the main conclusions of our work.

## 2 CLUSTER DATA BASE SELECTION

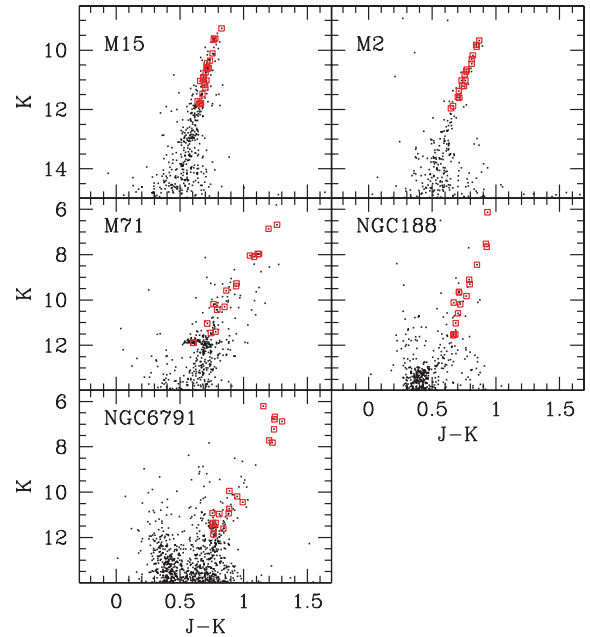
As we aim mainly at probing the impact of metallicity on the BC of stars at the low-temperature regime, a demanding constraint to set up our target sample was to explore a range as wide as possible in  $[\text{Fe}/\text{H}]$ , and pick up red giant stars with accurate measurements of their metallicity. The cluster population in the Galaxy naturally provided the ideal environment for our task. By combining globular and open clusters, one can easily span the whole metallicity range pertinent to Population I and II stars in our and in external galaxies. We therefore selected five template systems, namely the three metal-poor globular clusters M15, M2 and M71, and two metal-rich open clusters, NGC 188 and NGC 6791, such as to let metallicity span almost three orders of magnitude, from  $[\text{Fe}/\text{H}] = -2.3$  up to  $+0.4$ .

For each cluster, a subset of  $\sim 20$  suitable targets was then identified as among the brightest and coolest red giants from the 2MASS infrared c–m diagram (Skrutskie et al. 2006). In assembling the data set we also took care of picking up those objects from relatively uncrowded regions of the clusters, such as to reduce the chance of misidentification at the telescope.

The final set of target stars is summarized, for each cluster, in the five panels of Fig. 1 and in Tables 1–5. We eventually considered 92 stars in total, of which 21 are in M15, 18 in M2, 17 in M71, 16 in NGC 188 and 20 in NGC 6791, respectively. For each star, the tables always report the 2MASS id number (column 1) and the alternative cross-identification, according to other reference photometric catalogues, when available. The 2MASS J2000 coordinates on the sky and the corresponding  $J$ ,  $H$ ,  $K$  magnitudes are also always reported, together with a compilation of  $B$ ,  $V$ ,  $R_C$ ,  $I_C$  observed magnitudes according to the best reference catalogues for each cluster, as reported in the literature. When required, dereddened apparent magnitudes have been computed according to the colour excess  $E(B - V)$  as labelled in the header of each table.

## 3 OBSERVATIONS AND DATA REDUCTION

Spectroscopic observations of our stellar sample have been collected during several runs between 2003 June and October at the 3.5-m Telescopio Nazionale Galileo (TNG) of the Roque de los Muchachos Observatory, at La Palma (Canary Islands, Spain). A summary of the logbook can be found in Table 6.



**Figure 1.** Apparent c–m diagram of the five clusters included in our analysis, according to 2MASS  $J$  and  $K$  photometry. Big squares along the red giant branch mark the selected targets in our sample.

Optical spectroscopy was carried out with the LRS FOSC camera; a composite spectrum was collected for each target by matching a blue (grism LRB along the  $\lambda\lambda 3500$ – $8800$  Å wavelength range)<sup>3</sup> and a red set-up (grism LRR,  $\lambda\lambda 4500$ – $10\,300$  Å). In both cases the grisms provided a dispersion of  $2.8 \text{ Å pixel}^{-1}$  on a  $2048 \times 2048$  thinned and back-illuminated Loral CCD, with a  $13.5 \mu\text{m}$  pixel size. In order to collect the entire flux from target stars, we observed through a 5 arcsec wide slit; this condition actually made spectral resolution to be eventually constrained by the seeing figure (typically about 1–1.5 arcsec along the different nights), thus ranging between 10 and 15 Å [full width at half-maximum (FWHM)]. This is equivalent to a value of  $R = \lambda/\Delta\lambda$  of 600–1000. Whenever possible, and avoiding severe crowding conditions of the target fields, the longslit was located at the parallactic angle. Wavelength calibration and data reductions were performed following standard procedures.

The optical spectra have then been accompanied by the corresponding observations taken at infrared wavelength with the NICS camera at the Nasmyth focus of the TNG. The camera was coupled with a Rockwell  $1024 \times 1024$  Hawaii-1 HgCdTe detector. We took advantage of NICS unique design using the Amici grism coupled with two slits 0.5 and 5 arcsec wide, the latter being used for a complete flux sampling of the target stars. The spectra cover the entire wavelength range of  $8000 \text{ Å}$  to  $2.5 \mu\text{m}$  at a resolving power (for a 0.5 arcsec slit) varying between  $R = 80$  and 140 along the spectrum. In acquiring the spectra, the background subtraction and flat-fielding correction were eased by a standard dithering procedure on target images, while the wavelength calibration directly derived from the standard reference table providing the dispersion relation of the system. The MIDAS ESO package, and specifically its LONGSLIT

<sup>3</sup>Although nominally extended to  $9500 \text{ Å}$ , LRB spectra result is severely affected by second-order spectral emission in their red tail. For this reason, during data reduction, spectra have been clipped, retaining only the wavelength region blueward of  $8800 \text{ Å}$ .

**Table 1.** Cluster properties and stellar data base for cluster M15.

|                  |     |     | M15:        |             | $E(B - V) = 0.10$ |        | $[\text{Fe}/\text{H}] = -2.26$ |        |         |        |        |        |
|------------------|-----|-----|-------------|-------------|-------------------|--------|--------------------------------|--------|---------|--------|--------|--------|
| ID               |     |     | $\alpha$    | $\delta$    | $B$               | $V$    | $I_C$                          | $J$    | $H$     | $K$    |        |        |
| $a$              | $b$ | $c$ | (J2000.0)   |             | $b$               | $b$    | $c$                            | $b$    | $c$     | $a$    | $a$    | $a$    |
| 21300002+1209182 | 165 | 71  | 21:30:00.02 | 12:09:18.24 | 15.334            | 14.395 | 14.3460                        | 13.330 | 13.2709 | 12.479 | 11.926 | 11.824 |
| 21295705+1208531 | 959 | 6   | 21:29:57.06 | 12:08:53.11 | 14.549            | 13.426 | 13.4946                        | 12.144 | 12.2129 | 11.282 | 10.691 | 10.573 |
| 21295532+1210327 | 337 | 60  | 21:29:55.33 | 12:10:32.80 | 15.229            | 14.313 | 14.3694                        | 13.165 | 13.2132 | 12.452 | 11.899 | 11.786 |
| 21300090+1208571 | 558 | 461 | 21:30:00.91 | 12:08:57.13 | 14.092            | 12.700 | 12.9683                        | 11.281 | 11.4637 | 10.383 | 9.759  | 9.605  |
| 21295473+1208592 | 330 | 25  | 21:29:54.73 | 12:08:59.24 | 14.821            | 13.691 | 13.7581                        | 12.444 | 12.5006 | 11.591 | 11.065 | 10.906 |
| 21300461+1210327 | 369 |     | 21:30:04.62 | 12:10:32.73 | 14.851            | 13.836 |                                |        |         | 11.858 | 11.272 | 11.165 |
| 21295560+1212422 | 533 | 665 | 21:29:55.61 | 12:12:42.29 | 14.562            | 13.459 | 13.5218                        |        | 12.2237 | 11.336 | 10.723 | 10.609 |
| 21300514+1210041 | 372 |     | 21:30:05.15 | 12:10:04.18 | 15.186            | 14.288 |                                |        |         | 12.430 | 11.929 | 11.776 |
| 21295836+1209020 |     | 166 | 21:29:58.37 | 12:09:02.01 |                   |        | 13.8205                        |        | 12.5987 | 11.700 | 11.112 | 11.042 |
| 21295618+1210179 |     | 631 | 21:29:56.18 | 12:10:17.93 |                   |        | 12.7694                        |        | 11.3768 | 10.414 | 9.781  | 9.649  |
| 21295739+1209056 |     | 7   | 21:29:57.39 | 12:09:05.69 |                   |        | 13.7397                        |        | 12.5054 | 11.632 | 11.070 | 10.948 |
| 21300097+1210375 |     | 65  | 21:30:00.98 | 12:10:37.60 |                   |        | 13.8739                        |        | 12.6289 | 11.726 | 11.171 | 11.017 |
| 21300431+1210561 | 368 |     | 21:30:04.32 | 12:10:56.16 | 14.649            | 13.559 |                                |        |         | 11.459 | 10.893 | 10.757 |
| 21301049+1210061 | 621 |     | 21:30:10.49 | 12:10:06.18 | 14.563            | 13.406 |                                |        |         | 11.151 | 10.562 | 10.438 |
| 21300739+1210330 | 604 |     | 21:30:07.40 | 12:10:33.06 | 14.961            | 13.986 |                                |        |         | 11.964 | 11.399 | 11.264 |
| 21300569+1210156 |     |     | 21:30:05.70 | 12:10:15.68 |                   |        |                                |        |         | 12.156 | 11.596 | 11.480 |
| 21300553+1208553 |     |     | 21:30:05.54 | 12:08:55.35 |                   |        |                                |        |         | 12.357 | 11.835 | 11.719 |
| 21295756+1209438 |     |     | 21:29:57.57 | 12:09:43.85 |                   |        |                                |        |         | 10.096 | 9.429  | 9.269  |
| 21295082+1211301 |     |     | 21:29:50.83 | 12:11:30.18 |                   |        |                                |        |         | 11.326 | 10.725 | 10.612 |
| 21295881+1209285 |     | 59  | 21:29:58.82 | 12:09:28.59 |                   |        | 14.5465                        |        | 13.5061 | 11.088 | 10.568 | 10.353 |
| 21295716+1209175 |     | 273 | 21:29:57.17 | 12:09:17.52 |                   |        | 13.1662                        |        | 11.7880 | 10.867 | 10.220 | 10.112 |

<sup>a</sup>From 2MASS.

<sup>b</sup>From Cohen, Briley & Stetson (2005).

<sup>c</sup>From Rosenberg et al. (2000).

**Table 2.** Cluster properties and stellar data base for cluster M2.<sup>a</sup>

| M2:              |             | $E(B - V) = 0.06$ |        | $[\text{Fe}/\text{H}] = -1.62$ |        |
|------------------|-------------|-------------------|--------|--------------------------------|--------|
| ID               | $\alpha$    | $\delta$          | $J$    | $H$                            | $K$    |
|                  | (J2000.0)   |                   |        |                                |        |
| 21333827-0054569 | 21:33:38.28 | -00:54:56.92      | 10.542 | 9.827                          | 9.672  |
| 21333095-0052154 | 21:33:30.96 | -00:52:15.47      | 11.568 | 10.952                         | 10.814 |
| 21332468-0044252 | 21:33:24.69 | -00:44:25.21      | 12.549 | 12.006                         | 11.886 |
| 21331771-0047273 | 21:33:17.71 | -00:47:27.31      | 10.665 | 9.961                          | 9.821  |
| 21331723-0048171 | 21:33:17.24 | -00:48:17.10      | 11.112 | 10.429                         | 10.301 |
| 21331790-0048198 | 21:33:17.91 | -00:48:19.82      | 11.746 | 11.103                         | 11.017 |
| 21331854-0051563 | 21:33:18.55 | -00:51:56.33      | 11.779 | 11.137                         | 11.019 |
| 21331948-0051034 | 21:33:19.49 | -00:51:03.42      | 11.963 | 11.299                         | 11.214 |
| 21331923-0049058 | 21:33:19.23 | -00:49:05.84      | 12.280 | 11.695                         | 11.579 |
| 21332588-0046004 | 21:33:25.89 | -00:46:00.44      | 12.313 | 11.756                         | 11.600 |
| 21333668-0051058 | 21:33:36.68 | -00:51:05.89      | 10.730 | 10.026                         | 9.880  |
| 21333520-0046089 | 21:33:35.21 | -00:46:08.91      | 10.993 | 10.324                         | 10.174 |
| 21333488-0047572 | 21:33:34.88 | -00:47:57.25      | 11.265 | 10.589                         | 10.455 |
| 21333593-0049224 | 21:33:35.94 | -00:49:22.44      | 11.420 | 10.750                         | 10.650 |
| 21333432-0051285 | 21:33:34.33 | -00:51:28.50      | 11.490 | 10.828                         | 10.722 |
| 21332531-0052511 | 21:33:25.32 | -00:52:51.17      | 11.938 | 11.300                         | 11.203 |
| 21333109-0054522 | 21:33:31.09 | -00:54:52.28      | 12.086 | 11.526                         | 11.376 |
| 21333507-0051097 | 21:33:35.07 | -00:51:09.72      | 12.609 | 12.056                         | 11.962 |

<sup>a</sup>All the data are from 2MASS.

routine set, has been used for the whole reduction procedure, both for optical and infrared spectra.

### 3.1 Flux calibration

Given the nature of our investigation, special care has been devoted to suitably fluxing both optical and infrared spectra. This has been carried out by repeated observations, both with LRS and NICS, of

a grid of spectrophotometric standard stars from the list of Massey et al. (1988) and Hunt et al. (1998), as reported in Table 6. Note, however, that the lack of an appropriate SED calibration of standard stars along the entire wavelength range of our observations required a two-step procedure, relying on the direct observation of Vega as a primary calibrator, according to Tokunaga & Vacca (2005) results. Given the outstanding luminosity of this star we had to observe through a 10 mag neutral filter to avoid CCD saturation, and create

**Table 3.** Cluster properties and stellar data base for cluster M71.

| M71:             |          |          | $E(B - V) = 0.25$ |             | $[\text{Fe}/\text{H}] = -0.73$ |          |          |          |          |          |          |
|------------------|----------|----------|-------------------|-------------|--------------------------------|----------|----------|----------|----------|----------|----------|
| ID               | $\alpha$ | $\delta$ | $B$               | $V$         | $I_C$                          | $J$      | $H$      | $K$      |          |          |          |
| <i>a</i>         | <i>b</i> | <i>c</i> | (J2000.0)         | <i>b</i>    | <i>c</i>                       | <i>c</i> | <i>a</i> | <i>a</i> | <i>a</i> | <i>a</i> | <i>a</i> |
| 19535325+1846471 | 2672     | 256      | 19:53:53.25       | 18:46:47.13 | 13.905                         | 12.314   | 12.2085  | 10.3988  | 9.090    | 8.197    | 8.040    |
| 19534750+1846169 | 2222     | 540      | 19:53:47.51       | 18:46:16.99 | 14.431                         | 13.137   | 13.0010  | 11.5156  | 10.452   | 9.698    | 9.588    |
| 19535150+1848059 | 2541     | 892      | 19:53:51.50       | 18:48:05.91 | 14.079                         | 12.436   | 12.3250  | 10.4275  | 9.079    | 8.207    | 7.968    |
| 19535064+1849075 | 2461     | 331      | 19:53:50.64       | 18:49:07.52 | 14.466                         | 13.064   | 12.9955  | 11.4204  | 10.215   | 9.446    | 9.271    |
| 19534575+1847547 | 2079     | 648      | 19:53:45.76       | 18:47:54.80 | 14.247                         | 12.606   | 12.4924  | 10.5109  | 9.094    | 8.203    | 7.974    |
| 19534827+1848021 | 2281     | 309      | 19:53:48.27       | 18:48:02.17 | 14.078                         | 12.492   | 12.3636  | 10.5500  | 9.177    | 8.270    | 8.094    |
| 19534656+1847441 | 2145     | 46       | 19:53:46.57       | 18:47:44.19 | 14.838                         | 13.623   | 13.5524  | 12.2176  | 11.228   | 10.569   | 10.435   |
| 19535369+1846039 | 2711     | 172      | 19:53:53.70       | 18:46:03.98 | 15.527                         | 14.578   | 14.4974  | 13.3402  | 12.500   | 11.998   | 11.896   |
| 19534905+1846003 | 2337     | 303      | 19:53:49.05       | 18:46:00.34 | 14.601                         | 13.410   | 13.3436  | 11.9991  | 10.950   | 10.276   | 10.186   |
| 19534916+1846512 | 2347     | 6        | 19:53:49.16       | 18:46:51.22 | 14.997                         | 13.709   | 13.6219  | 12.2031  | 11.151   | 10.434   | 10.301   |
| 19534178+1848384 | 1772     |          | 19:53:41.79       | 18:48:38.46 | 15.877                         | 14.694   |          |          | 12.183   | 11.521   | 11.402   |
| 19535676+1845399 | 2921     |          | 19:53:56.77       | 18:45:39.95 | 15.747                         | 14.605   |          |          | 12.197   | 11.529   | 11.455   |
| 19533962+1848569 | 1611     |          | 19:53:39.62       | 18:48:56.99 | 15.695                         | 14.627   |          |          | 12.494   | 11.974   | 11.888   |
| 19533864+1847554 | 1543     |          | 19:53:38.64       | 18:47:55.45 | 15.475                         | 14.222   |          |          | 11.751   | 11.151   | 11.037   |
| 19534615+1847261 |          | 580      | 19:53:46.15       | 18:47:26.11 |                                |          | 13.1140  | 11.5109  | 10.336   | 9.543    | 9.395    |
| 19535610+1847167 | 2885     | 1066     | 19:53:56.10       | 18:47:16.76 | 13.577                         | 11.905   | 12.4009  | 9.2167   | 7.943    | 7.078    | 6.681    |
| 19534941+1844269 | 2365     |          | 19:53:49.41       | 18:44:26.98 | 13.863                         | 12.107   |          |          | 8.058    | 7.105    | 6.863    |

<sup>a</sup>From 2MASS.<sup>b</sup>From Geffert & Maintz (2000).<sup>c</sup>From Rosenberg et al. (2000).**Table 4.** Cluster properties and stellar data base for NGC 188.

| NGC 188:         |                  |             | $E(B - V) = 0.082$ |             | $[\text{Fe}/\text{H}] = -0.02$ |        |                   |        |        |        |        |        |        |
|------------------|------------------|-------------|--------------------|-------------|--------------------------------|--------|-------------------|--------|--------|--------|--------|--------|--------|
| ID               | $\alpha$         | $\delta$    | $B$                |             | $V$                            |        | $R_C$             | $I_C$  | $J$    | $H$    | $K$    |        |        |
| $a$              | $b$              | $c$         | (J2000.0)          |             | $b$                            | $c$    | $b$               | $c$    | $c$    | $c$    | $a$    | $a$    | $a$    |
| 00445253+8514055 | 4668             | N188-I-69   | 00:44:52.54        | 85:14:05.54 | 13.613                         | 13.579 | 12.319            | 12.357 | 11.598 | 11.087 | 10.098 | 9.461  | 9.304  |
| 00475922+8511322 | 5887             | N188-II-181 | 00:47:59.23        | 85:11:32.28 | 13.587                         | 13.428 | 12.135            | 12.197 | 11.429 | 10.894 | 9.891  | 9.203  | 9.100  |
| 00465966+8513157 | 5085             | N188-I-105  | 00:46:59.66        | 85:13:15.71 | 13.603                         | 13.538 | 12.362            | 12.422 | 11.732 | 11.269 | 10.349 | 9.789  | 9.639  |
| 00453697+8515084 | 5927             | N188-I-57   | 00:45:36.97        | 85:15:08.43 | 14.799                         | 14.760 | 13.658            | 13.706 | 13.039 | 12.571 | 11.709 | 11.149 | 11.024 |
| 00442946+8515093 | 4636             | N188-I-59   | 00:44:29.46        | 85:15:09.39 | 14.986                         | 14.950 | 14.005            | 14.046 | 13.385 | 12.962 | 12.202 | 11.653 | 11.520 |
| 00473222+8511024 | 5133             | N188-II-187 | 00:47:32.22        | 85:11:02.45 | 15.171                         | 15.132 | 14.077            | 14.140 | 13.490 | ...    | 12.234 | 11.700 | 11.567 |
| 00554526+8512209 | 6175             |             | 00:55:45.27        | 85:12:20.92 | 12.224                         | ...    | 10.834            | ...    | ...    | ...    | 8.441  | 7.631  | 7.520  |
| 00463920+8523336 | 4843             |             | 00:46:39.21        | 85:23:33.67 | 12.890                         | ...    | 11.569            | ...    | ...    | ...    | 9.292  | 8.597  | 8.441  |
| 00472975+8524140 | 4829             |             | 00:47:29.76        | 85:24:14.09 | 13.965                         | ...    | 12.781            | ...    | ...    | ...    | 10.783 | 10.210 | 10.114 |
| 00441241+8509312 | 4756             |             | 00:44:12.42        | 85:09:31.23 | 12.933                         | ...    | 11.404            | ...    | ...    | ...    | 8.580  | 7.892  | 7.652  |
| 00432696+8509175 | 4408             |             | 00:43:26.96        | 85:09:17.58 | 14.242                         | ...    | 13.199            | ...    | ...    | ...    | 11.293 | 10.706 | 10.591 |
| 00471847+8519456 | 4909             |             | 00:47:18.48        | 85:19:45.65 | 14.255                         | ...    | 13.010            | ...    | ...    | ...    | 10.908 | 10.289 | 10.187 |
| 00461981+8520086 | 4524             |             | 00:46:19.81        | 85:20:08.61 | 13.663                         | ...    | 12.468            | ...    | ...    | ...    | 10.385 | 9.816  | 9.674  |
| 00463004+8511518 | 5894             |             | 00:46:30.05        | 85:11:51.89 | 15.142                         | ...    | 14.052            | ...    | ...    | ...    | 12.185 | 11.695 | 11.518 |
| 00490560+8526077 | 5835             |             | 00:49:05.60        | 85:26:07.77 | 13.921                         | ...    | 12.717            | ...    | ...    | ...    | 10.594 | 9.956  | 9.825  |
| 00420323+8520492 | $\equiv$ SAO 109 |             | 00:42:03.23        | 85:20:49.23 | 11.40 <sup>d</sup>             |        | 9.89 <sup>d</sup> |        | ...    | ...    | 7.064  | 6.387  | 6.130  |

<sup>a</sup>From 2MASS.<sup>b</sup>From Platais et al. (2003).<sup>c</sup>From Stetson, McClure & Vandenberg (2004).<sup>d</sup> $B$  and  $V$  photometry from SIMBAD.

a secondary calibrator (namely HD 192281) observed both with and without the neutral density filter.

Concerning the applied correction for atmosphere absorption, we had to manage two delicate problems. From one hand, in fact, the intervening action of Sahara dust (the so-called ‘calima effect’) may abruptly increase the atmosphere opacity at optical wavelength. This is a recurrent feature for summer nights at La Palma, and it can severely affect the observing output, especially when dealing with absolute flux calibration. A careful check with repeated observations of the same standard stars along each night allowed us to assess

the presence of dust in the air. This confirmed, for instance, that along our observing runs, the night of 2003 August 7, displayed an outstanding (i.e. a factor of 4 higher than the average) dust extinction.

On the other hand, atmospheric water vapour can also play a role by affecting in unpredictable ways the infrared observations. Telluric H<sub>2</sub>O bands about 1.10, 1.38 and 1.88  $\mu\text{m}$  (Manduca & Bell 1979; Fuensalida & Alonso 1998), just restraining to the Amici wavelength range, may in fact strongly contaminate the *intrinsic* H<sub>2</sub>O absorption bands of stellar SED, especially for stars cooler

**Table 5.** Cluster properties and stellar data base for cluster NGC 6791.

| NGC 6791:        |          |          | $E(B - V) = 0.117$ |             | [Fe/H] = +0.4 |          |          |          |          |          |          |          |
|------------------|----------|----------|--------------------|-------------|---------------|----------|----------|----------|----------|----------|----------|----------|
| ID               | $\alpha$ | $\delta$ | $B$                |             | $V$           |          | $I_C$    | $J$      | $H$      | $K$      |          |          |
| <i>a</i>         | <i>b</i> | <i>c</i> | (J2000.0)          | <i>b</i>    | <i>c</i>      | <i>b</i> | <i>c</i> | <i>c</i> | <i>a</i> | <i>a</i> | <i>a</i> | <i>a</i> |
| 19210807+3747494 | 6697     | 3475     | 19:21:08.07        | 37:47:49.41 | 15.279        | 15.275   | 13.909   | 13.978   | 12.668   | 11.675   | 11.071   | 10.919   |
| 19204971+3743426 | 10 807   | 3502     | 19:20:49.72        | 37:43:42.67 | 15.554        | 15.563   | 13.956   | 13.982   | 10.990   | 9.041    | 8.167    | 7.815    |
| 19205259+3744281 | 10 140   | 2228     | 19:20:52.60        | 37:44:28.18 | 15.715        | 15.732   | 14.095   | 14.150   | 12.397   | 11.135   | 10.417   | 10.185   |
| 19205580+3742307 | 11 799   | 3574     | 19:20:55.81        | 37:42:30.75 | 16.307        | 16.297   | 14.934   | 14.957   | 13.609   | 12.622   | 11.993   | 11.860   |
| 19205671+3743074 | 11 308   | 2478     | 19:20:56.72        | 37:43:07.46 | 16.000        | 15.984   | 14.633   | 14.660   | 13.325   | 12.351   | 11.756   | 11.586   |
| 19210112+3742134 | 12 010   | 3407     | 19:21:01.12        | 37:42:13.45 | 15.942        | 15.928   | 14.433   | 14.455   | 12.901   | 11.821   | 11.130   | 10.938   |
| 19211606+3746462 | 7750     |          | 19:21:16.06        | 37:46:46.26 | 15.472        |          | 13.871   |          |          | 8.914    | 8.053    | 7.714    |
| 19213656+3740376 | 12 650   |          | 19:21:36.56        | 37:40:37.63 | 15.727        |          | 14.174   |          |          | 11.431   | 10.635   | 10.438   |
| 19210326+3741190 | 13 637   |          | 19:21:03.27        | 37:41:19.04 | 15.722        |          | 14.348   |          |          | 12.120   | 11.516   | 11.362   |
| 19213635+3739445 | 13 082   |          | 19:21:36.36        | 37:39:44.57 | 16.186        |          | 14.825   |          |          | 12.449   | 11.728   | 11.608   |
| 19212437+3735402 | 15 790   |          | 19:21:24.37        | 37:35:40.29 | 15.837        |          | 14.442   |          |          | 12.134   | 11.546   | 11.354   |
| 19212674+3735186 |          |          | 19:21:26.75        | 37:35:18.60 |               |          |          |          |          | 11.622   | 10.925   | 10.735   |
| 19211632+3752154 | 3254     |          | 19:21:16.32        | 37:52:15.46 | 15.282        |          | 13.998   |          |          | 11.776   | 11.068   | 10.967   |
| 19211176+3752459 | 2970     |          | 19:21:11.76        | 37:52:46.00 | 15.676        |          | 14.336   |          |          | 12.174   | 11.557   | 11.420   |
| 19202345+3754578 | 1829     |          | 19:20:23.45        | 37:54:57.82 | 14.592        |          | 12.866   |          |          | 8.029    | 7.133    | 6.787    |
| 19205149+3739334 |          |          | 19:20:51.50        | 37:39:33.44 |               |          |          |          |          | 7.356    | 6.516    | 6.201    |
| 19203285+3753488 | 2394     |          | 19:20:32.85        | 37:53:48.87 | 15.056        |          | 13.417   |          |          | 8.463    | 7.535    | 7.224    |
| 19200641+3744452 | 9800     |          | 19:20:06.42        | 37:44:45.28 | 14.670        |          | 13.307   |          |          | 10.831   | 10.094   | 9.943    |
| 19200882+3744317 | 10 034   |          | 19:20:08.83        | 37:44:31.71 | 15.353        |          | 13.710   |          |          | 7.916    | 6.989    | 6.670    |
| 19203219+3744208 | 10 223   |          | 19:20:32.20        | 37:44:20.81 | 16.421        |          | 14.854   |          |          | 8.176    | 7.262    | 6.874    |

<sup>a</sup>From 2MASS.

<sup>b</sup>From Kaluzny & Rucinski (1995).

<sup>c</sup>From Stetson, Bruntt & Grundahl (2003).

**Table 6.** Logbook of TNG observations along 2003.

| Obs. date<br>(2003) | Instrument | Targets              | Standards <sup>a</sup>                   |
|---------------------|------------|----------------------|------------------------------------------|
| July 29             | LRS        | NGC 6791             | HD 192281                                |
| July 30             | LRS        | NGC 6791             | HD 192281, SAO 48300, WOLF 1346          |
| July 31             | LRS        | NGC 6791             | HD 192281, SAO 48300, WOLF 1346          |
| August 6            | LRS        | M71                  | HD 192281, SAO 48300, WOLF 1346          |
| August 7            | LRS        | M15                  | HD 192281, SAO 48300, WOLF 1346          |
| August 11           | NICS       |                      | HD 192281, SAO 48300                     |
| August 12           | NICS       |                      | Vega                                     |
| August 18           | NICS       | M71                  | HD 192281                                |
| August 19           | NICS       |                      | Vega                                     |
| August 20           | NICS       | M15, M71,<br>NGC 188 | HD 192281, SAO 48300, WOLF 1346,<br>Vega |
| August 21           | LRS        | M2                   | HD 192281                                |
| August 23           | LRS        | M2, M15              | HD 192281                                |
| August 26           | LRS        | NGC 188              |                                          |
| August 27           | LRS        | NGC 188              | HD 192281                                |
| August 31           | NICS       | M71                  | HD 192281                                |
| September 1         | NICS       | M71, NGC 6791        | HD 192281                                |
| September 3         | NICS       | M2, M15, NGC 188     | SAO 48300                                |
| September 4         | NICS       | NGC 188              | HD 192281                                |
| September 5         | NICS       | NGC 188, NGC 6791    | HD 192281                                |
| October 14          | NICS       | M15                  | HD 192281                                |
| October 15          | NICS       | M2                   | HD 192281                                |

<sup>a</sup>HD 192281 and WOLF 1346 from optical calibration by Massey et al. (1988); SAO 48300 from *JHK* photometric calibration by Hunt et al. (1998); Vega from Tokunaga & Vacca (2005).

than 3500 K (Bertone et al. 2008). This effect may act on short time-scales along the night, so that it cannot be reconducted to an average nightly extinction curve, as for optical observations. The H<sub>2</sub>O contamination in each spectrum was therefore corrected

by rescaling the average extinction curve to minimize the residual water vapour feature in the stellar spectra.

Overall, the full calibration procedure led us to consistently assemble the LRB–LRR–Amici spectral branches and obtain a

nominal SED of target stars along the 3450–25 000 Å wavelength range. However, just an eye inspection of the full spectra made evident in some cases a residual systematic component causing a ‘glitch’ at the boundary connection between LRS and NICS observations. Clearly, this effect urged us to further refine our analysis, taking into account the supplementary photometric piece of information, as we will discuss in more detail in the next section.

### 3.2 Photometry and spectral ‘fine tuning’

The relevant data base of broad-band photometry available in the literature for all stars in our sample can be usefully accounted for in our analysis as a supplementary tool to tackle the inherent difficulty in reproducing the overall shape of stellar SED at the required accuracy level over the entire range of our observations.

As summarized in Tables 1–5, a wide collection of photometric catalogues can be considered, providing multicolour photometry along the range spanned by LRS and NICS spectra. Facing the observed values, one can similarly derive a corresponding set of multicolour synthetic magnitudes relying on the assembled SED of each star. Operationally, from our  $f(\lambda)$  values we need to numerically assess the quantity

$$m_{\text{syn}}^j = -2.5 \log \frac{\int f(\lambda) S(\lambda)^j d\lambda}{\int S(\lambda)^j d\lambda} - 2.5 \log f_0^j \quad (3)$$

being  $m_{\text{syn}}^j$  the synthetic magnitude in the  $j$ th photometric band, identified by a filter response  $S(\lambda)^j$  and a calibrating zero-point flux  $f_0^j$ . For our calculations we relied on the Buzzoni (2005) reference data (see table 1 therein).

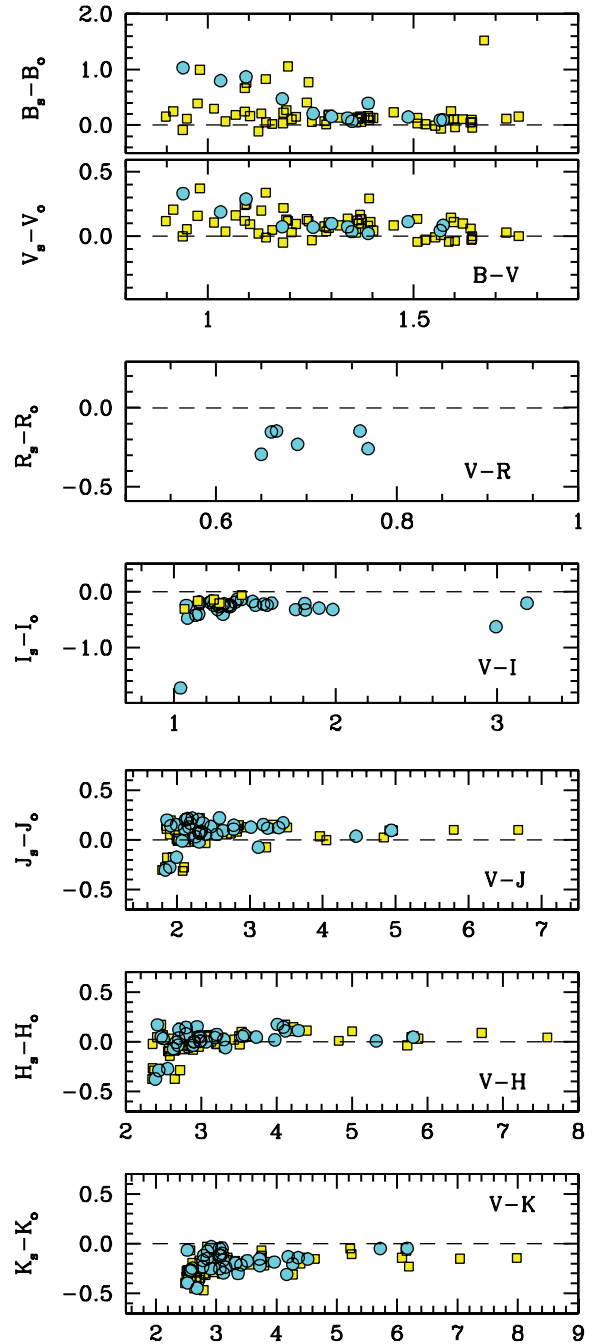
A comparison of our output with the available photometry is displayed in Fig. 2. The magnitude difference (in the sense ‘synthetic’ – ‘observed’) is plotted in the different panels of the figure versus *observed* colour, according to the different photometric catalogues quoted in Tables 1–5. As typically two sources for  $V$  magnitudes are available for most clusters, the observed colours have been computed for each available  $V$  data set and are displayed with a different marker (either dot or square) in the plots.

Just a glance to Fig. 2 makes it evident that systematic offsets are present between observed photometry and synthetic magnitudes. This may partly be due to zero-point uncertainty in computing equation (3), as well as to residual systematic drifts inherent to our spectral flux calibration. In addition, from the figure one has also to report a few outliers in every band, and a notably skewed distribution of  $B$  residuals. To recover for this systematics, we devised an iterative  $3\sigma$  clipping procedure on the data of Fig. 2 to reject deviant stars and lead synthetic magnitudes to match the standard photometric system of the observed catalogues. Our results are displayed in graphical form in the plots of Fig. 3.

After just a few rejections, our procedure quickly converged to mean magnitude offsets ( $\langle \text{obs} - \text{syn} \rangle$ ; see Table 7) to correct equation (3) output. After correction for this systematics, our final synthetic photometry of cluster stars (not accounting for Galactic reddening) is collected in Tables 8 and 9. According to Table 7, note that a  $\sigma = 0.095$  mag in total magnitude residuals evidently implies an *internal* accuracy in our spectral flux calibration of target stars better than 10 per cent.

### 3.3 Stellar outliers

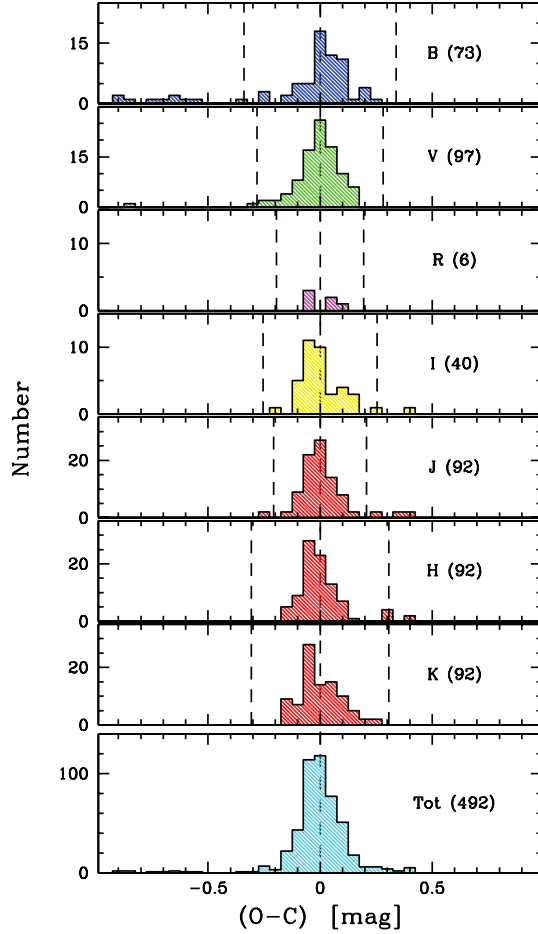
It could be interesting to analyse in some detail the deviant stars in our  $\Delta m$  clipping procedure in order to collect further clues about their nature. Apart from the obvious impact of photometric errors,



**Figure 2.** The  $B$ ,  $V$ ,  $R$ ,  $I$ ,  $J$ ,  $H$ ,  $K$  magnitude residuals between synthetic and observed magnitudes (in the sense ‘syn’ – ‘obs’) for the 94 stars in our sample, plotted versus literature colours, according to the data of Tables 1–5. Synthetic magnitudes derived from the numerical integration of the observed SED with the Johnson–Cousins filters. All the available photometry has been accounted for. Some stars with multiple  $V$  data sets appear, therefore, twice in the plots and are singled out by dot and square markers, respectively.

$3\sigma$  outliers may in fact more likely be displaying signs of an intrinsic physical variability in their luminosity.

As summarized in Table 10, in total 10 stars have been found to significantly ( $>3\sigma$ ) deviate from the literature compilations. A careful check of their identifications on the SIMBAD data base indicates that at least three of them are known variables (typically



**Figure 3.** The histogram of magnitude residuals for the data of Fig. 2, after correction for the systematic offsets, according to Table 7. A total of 492 measures have been accounted for, as labelled in the global histogram of the bottom panel, including multiple photometry sources in the literature from Tables 1–5. Dashed vertical lines mark the  $\pm 3\sigma$  clipping edges, according to our iterative procedure, as devised in Section 3.2. Mag residuals are in the sense ‘obs’ – ‘syn’. After outliers rejections, the global sample of 458 measurements has, on average,  $\sigma(\Delta\text{mag}) = \pm 0.095$  (see Table 7).

**Table 7.** Magnitude residuals between observed and theoretical magnitudes.<sup>a</sup>

| Band                 | All the clusters                          |          | $N_{\text{in}}$ | $N_{\text{out}}$ |
|----------------------|-------------------------------------------|----------|-----------------|------------------|
|                      | $\langle \text{obs} - \text{syn} \rangle$ | $\sigma$ |                 |                  |
| <i>B</i>             | −0.137                                    | 0.113    | 63              | 10               |
| <i>V</i>             | −0.091                                    | 0.094    | 72              | 1                |
| <i>R<sub>C</sub></i> | +0.205                                    | 0.065    | 6               | –                |
| <i>I<sub>C</sub></i> | +0.244                                    | 0.085    | 38              | 2                |
| <i>J</i>             | −0.093                                    | 0.069    | 88              | 9                |
| <i>H</i>             | −0.012                                    | 0.102    | 94              | 3                |
| <i>K</i>             | +0.197                                    | 0.102    | 97              | –                |
| Total                | 0.000 <sup>b</sup>                        | 0.095    | 458             | 25               |

<sup>a</sup>Magnitude residuals are in the sense of observed – synthetic one.

<sup>b</sup>Weighting with the number of entries,  $N_{\text{in}}$ .

semiregulars or irregulars, as expected for their nature of late-type red giants).<sup>4</sup> No firm conclusions can be drawn, on the contrary, for the other seven cases, although it is evident even from a colour check (see Fig. 4) that they have been picked up in an intrinsically different status with respect to previous data in the literature.<sup>5</sup> We therefore commend the stars in the list of Table 10 as special candidates for further in-depth investigations for variability.

#### 4 SPECTRAL ENERGY DISTRIBUTION AND BOLOMETRIC LUMINOSITY

The synthetic photometric catalogues obtained from the observed spectral data base had a twofold aim: first, this procedure allowed us to self-consistently match broad-band magnitudes with the inferred measure of  $m_{\text{bol}}$  in order to obtain the corresponding value of the bolometric correction; secondly, the study of the magnitude residuals with respect to the literature data provided us with the appropriate offsets in flux rescaling such as to ‘smoothly’ connect our optical and infrared spectra and lead therefore to a more accurate estimate of  $m_{\text{bol}}$ .

Operationally, for the latter task, we proceeded as follows. Taking into account the individual set of  $(\text{obs} - \text{syn})$  magnitude residuals, for each star in our sample we computed a mean optical and infrared offset ( $\Delta m_{\text{LRS}}$  and  $\Delta m_{\text{NICS}}$ , respectively) by separately averaging the *B*, *V*, *R<sub>C</sub>*, *I<sub>C</sub>* and *J*, *H*, *K* mag residuals. The LRS spectra and the NICS observations have then been matched by multiplying visual and IR fluxes by a factor of  $10^{-0.4(\Delta m_{\text{LRS}})}$  and  $10^{-0.4(\Delta m_{\text{NICS}})}$ , respectively. Foreground reddening has been corrected relying on the standard relation  $k(\lambda) = A(\lambda)/E(B - V)$  (Scheffler 2006), where the appropriate value of the colour excess  $E(B - V)$  is from the headers of Tables 1–5. In its final form, the SED is reshaped such as  $f_0(\lambda) = f(\lambda) 10^{0.4 k(\lambda) E(B - V)}$ .

The LRS and NICS spectra have been connected at 8800 Å, by smoothing the wavelength region between 7800 and 10000 Å (in order to gain S/N, especially for LRS poor signal at the long wavelength edge). In Fig. 5, we summarize our results for an illustrative set of SEDs by picking up for each cluster the brightest (i.e. roughly the coolest) and faintest (i.e. warmest) stars in our sample.<sup>6</sup> Note, from the figure, the striking presence of the CO bump at about 1.6 μm (Frogel et al. 1978; Lançon & Mouhcine 2002), as well as the broad H<sub>2</sub>O absorption bands to which the sharper (and variable) emission of telluric water vapour superposes (see, in particular, the case of M15 stars in the figure). This made far more difficult any accurate cleaning procedure, as we discussed in Section 3.1.

##### 4.1 Temperature scale

Although sampled over a wide wavelength range, SED of our stars still lacks the contribution of ultraviolet and far-infrared luminosity.

<sup>4</sup>Note, on the other hand, the counter-example of star #2156 in NGC 6791, known as Irr variable V70 ≡ SBG 2240 (Mochejska, Stanek & Kaluzny 2003) and not a deviant in our spectroscopic observations.

<sup>5</sup>Curiously enough, however, one may note that six out of the seven remaining objects are all located in NGC 188, and are both *B* and *J* outliers. Both photometric bands actually cover the ‘bluer’ wavelength regions of both the LRS and NICS spectra, respectively. This coincidence might perhaps indicate some hidden problem with the flux calibration procedure during the observation of this cluster.

<sup>6</sup>For the interested reader, the entire spectral data base is available in electronic form upon request, or directly on the web at the authors’ web site <http://www.bo.astro.it/~eps/home.html>

**Table 8.** Standard synthetic photometry from SED of target stars in globular clusters M71, M15 and M2.<sup>a</sup>

| ID                            | M15      |          |                      |                      |          |          |          |
|-------------------------------|----------|----------|----------------------|----------------------|----------|----------|----------|
|                               | <i>B</i> | <i>V</i> | <i>R<sub>C</sub></i> | <i>I<sub>C</sub></i> | <i>J</i> | <i>H</i> | <i>K</i> |
| 21300002+1209182              | 15.11    | 14.30    | 13.81                | 13.27                | 12.58    | 12.08    | 11.95    |
| 21295705+1208531              | 14.30    | 13.35    | 12.79                | 12.18                | 11.41    | 10.82    | 10.74    |
| 21295532+1210327              | 15.34    | 14.43    | 13.85                | 13.24                | 12.50    | 11.94    | 11.72    |
| 21300090+1208571              | 14.04    | 12.90    | 12.21                | 11.47                | 10.51    | 9.82     | 9.50     |
| 21295473+1208592              | 14.89    | 13.80    | 13.19                | 12.55                | 11.62    | 11.02    | 10.95    |
| 21300461+1210327              | 15.01    | 13.85    | 13.24                | 12.62                | 11.86    | 11.16    | 10.98    |
| 21295560+1212422              | 14.59    | 13.46    | 12.86                | 12.23                | 11.41    | 10.79    | 10.55    |
| 21300514+1210041              | 15.20    | 14.31    | 13.79                | 13.23                | 12.45    | 11.89    | 11.64    |
| 21295836+1209020              | 14.80    | 13.83    | 13.27                | 12.65                | 11.81    | 11.22    | 11.01    |
| 21295618+1210179              | 14.02    | 12.89    | 12.19                | 11.48                | 10.49    | 9.82     | 9.55     |
| 21295739+1209056              | 14.89    | 13.83    | 13.22                | 12.58                | 11.65    | 11.05    | 11.03    |
| 21300097+1210375              | 14.91    | 13.85    | 13.24                | 12.63                | 11.85    | 11.19    | 11.14    |
| 21300431+1210561              | 14.76    | 13.59    | 12.91                | 12.25                | 11.40    | 10.81    | 10.65    |
| 21301049+1210061              | 14.45    | 13.36    | 12.73                | 12.09                | 11.25    | 10.60    | 10.35    |
| 21300739+1210330              | 15.22    | 14.05    | 13.36                | 12.67                | 11.86    | 11.24    | 11.10    |
| 21300569+1210156              | 15.02    | 14.11    | 13.56                | 12.97                | 12.21    | 11.61    | 11.50    |
| 21300553+1208553              | 15.82    | 14.84    | 14.26                | 13.61                | 12.50    | 11.86    | 11.65    |
| 21295756+1209438              | 13.80    | 12.45    | 11.72                | 11.01                | 10.10    | 9.47     | 9.32     |
| 21295082+1211301              | 14.61    | 13.52    | 12.91                | 12.27                | 11.40    | 10.82    | 10.66    |
| 21295881+1209285 <sup>b</sup> | 14.62    | 13.40    | 12.70                | 12.03                | 11.17    | 10.57    | 10.42    |
| 21295716+1209175              | 13.96    | 13.03    | 12.45                | 11.84                | 10.98    | 10.36    | 10.20    |
| ID                            | M2       |          |                      |                      |          |          |          |
|                               | <i>B</i> | <i>V</i> | <i>R<sub>C</sub></i> | <i>I<sub>C</sub></i> | <i>J</i> | <i>H</i> | <i>K</i> |
| 21333827−0054569              | 13.71    | 12.72    | 12.17                | 11.58                | 10.55    | 9.85     | 9.73     |
| 21333095−0052154              | 14.74    | 13.68    | 13.11                | 12.53                | 11.59    | 10.96    | 10.87    |
| 21332468−0044252              | 15.71    | 14.65    | 14.07                | 13.48                | 12.59    | 12.01    | 11.94    |
| 21331771−0047273              | 14.30    | 13.02    | 12.32                | 11.66                | 10.69    | 9.94     | 9.91     |
| 21331723−0048171              | 15.06    | 13.66    | 12.91                | 12.21                | 11.18    | 10.44    | 10.32    |
| 21331790−0048198              | 15.87    | 14.74    | 14.17                | 13.54                | 12.00    | 11.05    | 10.90    |
| 21331854−0051563              | 14.88    | 13.89    | 13.32                | 12.72                | 11.80    | 11.17    | 11.06    |
| 21331948−0051034              | 15.11    | 14.12    | 13.55                | 12.93                | 12.01    | 11.38    | 11.17    |
| 21331923−0049058              | 16.49    | 15.21    | 14.58                | 13.91                | 12.52    | 11.67    | 11.46    |
| 21332588−0046004              | 15.42    | 14.44    | 13.89                | 13.33                | 12.40    | 11.78    | 11.59    |
| 21333668−0051058              | 14.35    | 13.12    | 12.47                | 11.81                | 10.76    | 10.05    | 9.92     |
| 21333520−0046089              | 14.58    | 13.36    | 12.70                | 12.04                | 11.02    | 10.34    | 10.23    |
| 21333488−0047572              | 14.98    | 13.67    | 12.98                | 12.30                | 11.33    | 10.64    | 10.42    |
| 21333593−0049224              | 15.31    | 13.93    | 13.18                | 12.48                | 11.49    | 10.82    | 10.60    |
| 21333432−0051285              | 14.89    | 13.72    | 13.09                | 12.45                | 11.50    | 10.87    | 10.77    |
| 21332531−0052511              | 15.26    | 14.11    | 13.51                | 12.90                | 11.98    | 11.38    | 11.18    |
| 21333109−0054522              | 15.98    | 14.57    | 13.80                | 13.08                | 12.15    | 11.56    | 11.37    |
| 21333507−0051097              | 15.94    | 14.78    | 14.14                | 13.52                | 12.63    | 12.07    | 12.02    |
| ID                            | M71      |          |                      |                      |          |          |          |
|                               | <i>B</i> | <i>V</i> | <i>R<sub>C</sub></i> | <i>I<sub>C</sub></i> | <i>J</i> | <i>H</i> | <i>K</i> |
| 19535325+1846471              | 14.02    | 12.37    | 11.42                | 10.43                | 8.92     | 8.36     | 7.93     |
| 19534750+1846169              | 14.48    | 13.11    | 12.36                | 11.59                | 10.41    | 9.71     | 9.57     |
| 19535150+1848059              | 13.99    | 12.32    | 11.34                | 10.38                | 9.10     | 8.30     | 8.02     |
| 19535064+1849075              | 14.46    | 13.02    | 12.22                | 11.42                | 10.27    | 9.49     | 9.25     |
| 19534575+1847547              | 14.21    | 12.48    | 11.45                | 10.43                | 9.12     | 8.30     | 8.02     |
| 19534827+1848021              | 14.04    | 12.36    | 11.40                | 10.47                | 9.24     | 8.41     | 8.09     |
| 19534656+1847441              | 14.85    | 13.63    | 12.93                | 12.21                | 11.22    | 10.56    | 10.47    |
| 19535369+1846039              | 15.50    | 14.54    | 14.01                | 13.40                | 12.56    | 12.02    | 11.85    |
| 19534905+1846003              | 14.73    | 13.45    | 12.75                | 12.01                | 10.91    | 10.26    | 10.15    |
| 19534916+1846512              | 14.87    | 13.65    | 13.01                | 12.30                | 11.19    | 10.46    | 10.30    |
| 19534178+1848384              | 15.77    | 14.55    | 13.87                | 13.17                | 12.24    | 11.58    | 11.40    |
| 19535676+1845399              | 15.66    | 14.50    | 13.86                | 13.18                | 12.22    | 11.58    | 11.43    |
| 19533962+1848569              | 15.74    | 14.70    | 14.13                | 13.50                | 12.50    | 11.87    | 11.74    |
| 19533864+1847554              | 15.39    | 14.10    | 13.42                | 12.72                | 11.72    | 11.19    | 11.09    |
| 19534615+1847261              | 14.68    | 13.21    | 12.38                | 11.55                | 10.35    | 9.60     | 9.44     |
| 19535610+1847167 <sup>c</sup> | 14.96    | 13.27    | 11.21                | 9.26                 | 7.89     | 7.08     | 6.83     |
| 19534941+1844269 <sup>d</sup> | 13.88    | 12.02    | 10.71                | 9.42                 | 7.96     | 7.20     | 6.96     |

<sup>a</sup>After correction for the systematic offsets, according to Table 7.<sup>b</sup>Dropped: *I* outlier.<sup>c</sup>Dropped: SR variable Z Sge; *B*, *V* outlier.<sup>d</sup>Var AN 48.1928 (Baade 1928).

**Table 9.** Standard synthetic photometry from SED of target stars in open clusters NGC 188 and NGC 6791.<sup>a</sup>

| NGC 188                       |          |          |                      |                      |          |          |          |
|-------------------------------|----------|----------|----------------------|----------------------|----------|----------|----------|
| ID                            | <i>B</i> | <i>V</i> | <i>R<sub>C</sub></i> | <i>I<sub>C</sub></i> | <i>J</i> | <i>H</i> | <i>K</i> |
| 00445253+8514055              | 13.65    | 12.34    | 11.66                | 11.01                | 10.04    | 9.41     | 9.45     |
| 00475922+8511322              | 13.68    | 12.13    | 11.38                | 10.73                | 9.78     | 9.20     | 9.25     |
| 00465966+8513157              | 13.87    | 12.40    | 11.71                | 11.11                | 10.25    | 9.71     | 9.67     |
| 00453697+8515084 <sup>b</sup> | 15.49    | 13.90    | 13.10                | 12.40                | 11.44    | 10.87    | 10.77    |
| 00442946+8515093 <sup>c</sup> | 15.84    | 14.28    | 13.44                | 12.73                | 11.81    | 11.27    | 11.32    |
| 00473222+8511024 <sup>d</sup> | 15.79    | 14.24    | 13.40                | 12.73                | 11.87    | 11.40    | 11.49    |
| 00554526+8512209              | 12.25    | 10.82    | 10.06                | 9.34                 | 8.31     | 7.59     | 7.54     |
| 00463920+8523336              | 12.89    | 11.56    | 10.87                | 10.21                | 9.19     | 8.53     | 8.50     |
| 00472975+8524140              | 14.05    | 12.91    | 12.33                | 11.74                | 10.70    | 10.11    | 9.98     |
| 00441241+8509312              | 12.81    | 11.28    | 10.45                | 9.68                 | 8.60     | 7.85     | 7.78     |
| 00432696+8509175              | 14.17    | 13.14    | 12.61                | 12.08                | 11.25    | 10.76    | 10.59    |
| 00471847+8519456 <sup>e</sup> | 14.89    | 13.03    | 12.19                | 11.47                | 10.54    | 9.99     | 10.07    |
| 00461981+8520086 <sup>f</sup> | 14.58    | 12.50    | 11.60                | 10.88                | 9.98     | 9.43     | 9.40     |
| 00463004+8511518 <sup>g</sup> | 15.67    | 14.20    | 13.45                | 12.78                | 11.91    | 11.42    | 11.38    |
| 00490560+8526077              | 13.89    | 12.65    | 12.02                | 11.41                | 10.48    | 9.90     | 9.97     |
| 00420323+8520492              | 11.29    | 9.75     | 8.91                 | 8.14                 | 7.05     | 6.43     | 6.20     |
| NGC 6791                      |          |          |                      |                      |          |          |          |
| 19210807+3747494              | 15.29    | 13.98    | 13.33                | 12.70                | 11.66    | 11.06    | 10.87    |
| 19204971+3743426 <sup>h</sup> | 15.52    | 13.97    | 12.31                | 10.61                | 9.04     | 8.20     | 7.97     |
| 19205259+3744281              | 15.69    | 14.10    | 13.19                | 12.32                | 11.17    | 10.45    | 10.20    |
| 19205580+3742307              | 16.23    | 14.90    | 14.23                | 13.59                | 12.61    | 12.03    | 11.96    |
| 19205671+3743074              | 15.97    | 14.64    | 13.96                | 13.31                | 12.32    | 11.74    | 11.66    |
| 19210112+3742134              | 15.94    | 14.48    | 13.68                | 12.92                | 11.82    | 11.06    | 10.96    |
| 19211606+3746462              | 15.29    | 13.74    | 12.11                | 10.45                | 8.91     | 8.10     | 7.84     |
| 19213656+3740376              | 15.58    | 14.07    | 13.24                | 12.46                | 11.40    | 10.72    | 10.50    |
| 19210326+3741190              | 15.72    | 14.39    | 13.69                | 13.01                | 12.03    | 11.44    | 11.36    |
| 19213635+3739445              | 16.10    | 14.76    | 14.11                | 13.49                | 12.47    | 11.78    | 11.58    |
| 19212437+3735402              | 15.83    | 14.46    | 13.79                | 13.15                | 12.14    | 11.45    | 11.30    |
| 19212674+3735186              | 15.33    | 13.98    | 13.25                | 12.56                | 11.59    | 10.99    | 10.79    |
| 19211632+3752154              | 15.22    | 13.98    | 13.32                | 12.67                | 11.71    | 11.12    | 10.93    |
| 19211176+3752459              | 15.65    | 14.38    | 13.73                | 13.11                | 12.13    | 11.47    | 11.41    |
| 19202345+3754578              | 14.57    | 12.80    | 11.43                | 9.63                 | 7.96     | 7.08     | 6.84     |
| 19205149+3739334              | 13.26    | 11.66    | 10.23                | 8.75                 | 7.35     | 6.58     | 6.23     |
| 19203285+3753488              | 14.97    | 13.39    | 11.67                | 10.00                | 8.46     | 7.55     | 7.19     |
| 19200641+3744452              | 14.67    | 13.34    | 12.61                | 11.89                | 10.79    | 10.06    | 9.87     |
| 19200882+3744317              | 15.17    | 13.62    | 11.61                | 9.67                 | 7.92     | 7.07     | 6.72     |
| 19203219+3744208 <sup>i</sup> | 16.22    | 14.77    | 12.46                | 10.23                | 8.18     | 7.29     | 6.93     |

<sup>a</sup>After correction for the systematic offsets, according to Table 7.

<sup>b</sup>Dropped: *B*, *J* outlier.

<sup>c</sup>Dropped: *B*, *J*, *H* outlier.

<sup>d</sup>Dropped: *B*, *J* outlier.

<sup>e</sup>Dropped: *B*, *J* outlier.

<sup>f</sup>Dropped: *B*, *J*, *H* outlier.

<sup>g</sup>Dropped: *B*, *J* outlier.

<sup>h</sup>Dropped: *I* outlier; V13 - Var? (de Marchi et al. 2007).

<sup>i</sup>V70 ≡ SBG 2240: Irr var (Mochejska et al. 2003).

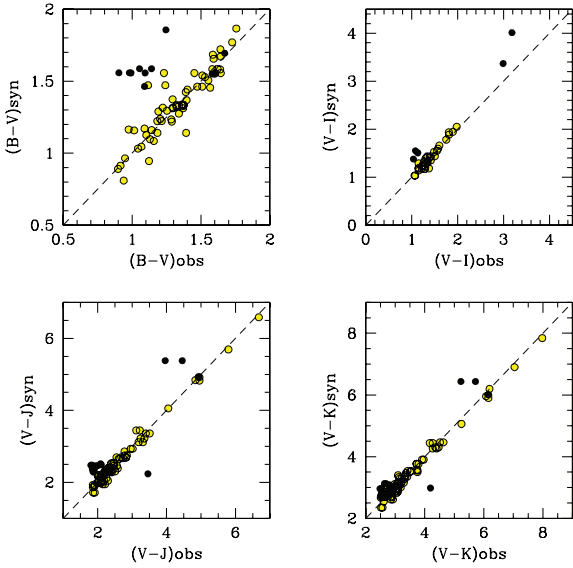
Clearly, a safe assessment of this contribution is mandatory to lead to a confident measure of the bolometric magnitude. As the amount of energy released outside the spectral window of our observations critically depends on stellar temperature, our task to compute BC requires in fact a parallel calibration of  $T_{\text{eff}}$  in the range of our red giant stars.

Among the many outstanding efforts in this direction, we have to recall the works of Flower (1975), Bessell (1979), Blackwell, Petford & Shallis (1980), Ridgway et al. (1980), Bessell et al. (1998), Houdashelt et al. (2000), VandenBerg & Clem (2003), Bertone et al. (2004) and Worthey & Lee (2006). In their exhaustive

analysis, Alonso et al. (1999) provided an accurate analytical set of fitting functions that calibrate stellar effective temperature versus Johnson/Cousins broad-band colours. The Alonso et al. (1999) calibration relies on the IRFM estimate of stellar surface brightness, and considers stars of spectral type K5 or earlier, spanning a wide metallicity range ( $-3.0 \lesssim [\text{Fe}/\text{H}] \lesssim +0.2$ ). Within this range, the Alonso et al. claim that the internal accuracy in the definition of  $T_{\text{eff}}$  is better than 5 per cent. As a further important result of their work, some colours, like  $(V - I)$ ,  $(V - L')$ ,  $(J - K)$  and  $(I - K)$  are found to be fair tracers of temperature, almost independently of stellar metallicity.

**Table 10.** Stellar outliers of our sample in the different photometric bands.

| Cluster | ID   | Outlier in |          |                      |                      |          |          |          | Notes                       |
|---------|------|------------|----------|----------------------|----------------------|----------|----------|----------|-----------------------------|
|         |      | <i>B</i>   | <i>V</i> | <i>R<sub>C</sub></i> | <i>I<sub>C</sub></i> | <i>J</i> | <i>H</i> | <i>K</i> |                             |
| M15     | 180  | ...        | ...      | ...                  | x                    | ...      | ...      | ...      | ...                         |
| M71     | 4212 | x          | x        | ...                  | ...                  | ...      | ...      | ...      | Z Sge - SRa P $\sim$ 175 d  |
|         | 5755 | ...        | ...      | ...                  | x                    | ...      | ...      | ...      | V2 $\equiv$ AN 48.1928 - Ir |
| N188    | 567  | x          | ...      | ...                  | ...                  | x        | ...      | ...      | ...                         |
|         | 652  | x          | ...      | ...                  | ...                  | x        | x        | ...      | ...                         |
|         | 1109 | x          | ...      | ...                  | ...                  | x        | ...      | ...      | ...                         |
|         | 630  | x          | ...      | ...                  | ...                  | x        | ...      | ...      | ...                         |
|         | 174  | x          | ...      | ...                  | ...                  | x        | x        | ...      | ...                         |
|         | 1352 | x          | ...      | ...                  | ...                  | x        | ...      | ...      | ...                         |
| N6791   | 3502 | ...        | ...      | ...                  | x                    | ...      | ...      | ...      | V13 - Var?                  |
| Total   |      | 7          | 1        | 0                    | 3                    | 6        | 2        | 0        |                             |

**Figure 4.** Colour distribution of photometric outliers, according to our  $3\sigma$  clipping procedure (see Fig. 3). Target location for the whole star sample in the synthetic versus observed colour planes are displayed, with dark solid dots marking the ‘dropped’ objects (see Table 10).

The Alonso et al. (1999) calibration, however, applies strictly to stars warmer than  $\sim 4000$  K, while our stellar sample definitely spans a wider colour range. This is certainly the case, for instance, of the brightest giant stars in NGC 6791, too (infra)red to match the Alonso et al. fitting functions. For these cases one could rely on the wider validity range of the  $(B - V)$  calibration, although the advantage may only be a nominal one as any optical colour, like  $(B - V)$ , tends naturally to saturate when moving to  $T_{\text{eff}} \lesssim 4000$  K (Johnson 1966, see also fig. 2 in Alonso et al. 1999).

Considering the whole set of the Alonso et al. fitting functions, we eventually chose four reference colours to assess the value of effective temperature for our stars. Two colours, namely  $(B - V)$  and  $(J - K)$ , are entirely comprised within the LRS and NICS spectral branches, respectively, and they can therefore ostensibly probe the shape of SED in a more self-consistent way. To these two colours we also added  $(V - I_C)$  and  $(V - K)$ , as they provided a check of our flux calibration bridging the optical and infrared regions of the spectra.

Dereddened colours for each star in our sample eventually provided a set of nominal values of  $T_{\text{eff}}$ , by entering the appropriate

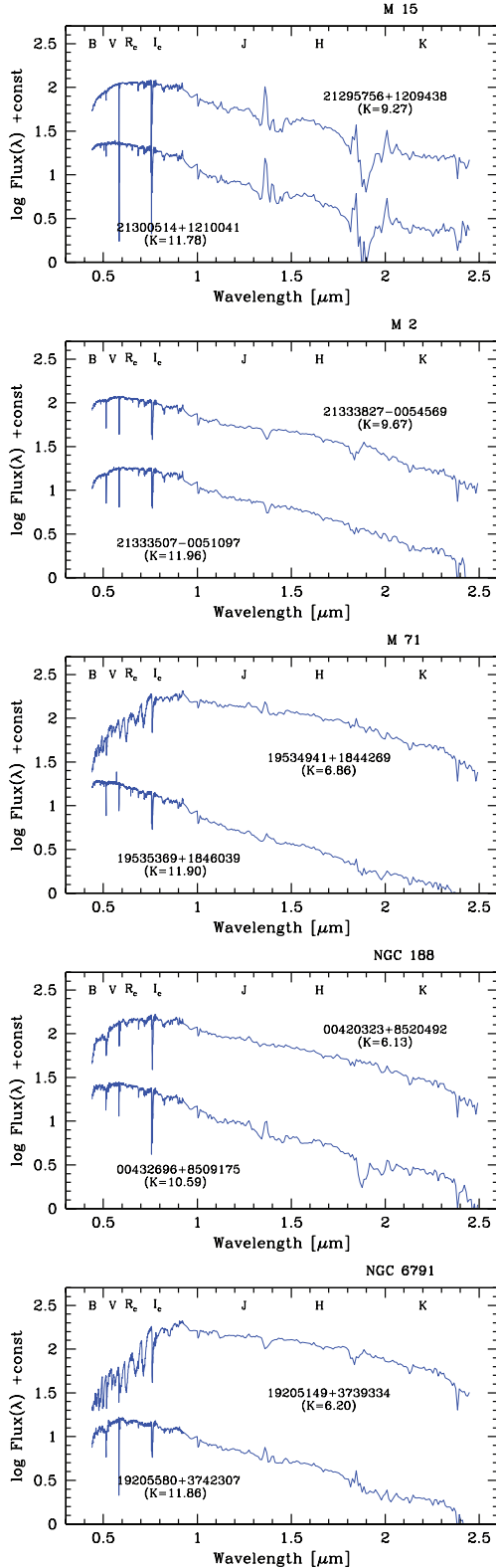
fitting functions. The ‘allowed’ values of  $T_{\text{eff}}$  (i.e. if comprised within the boundary limits of the adopted calibration functions) were then averaged, deriving the mean fiducial value of the effective temperature, reported in Tables 11 and 12 (column 10). In case of just one  $T_{\text{eff}}$  estimate [typically from  $(J - K)$  colour], we also added the  $(V - K)$  output (reported in italics in the tables) trusting on a fairly smooth trend of the Alonso et al. (1999) calibration for this colour, when extrapolated to cooler temperatures (see figs 8 and 10 therein).

Once combining the different temperature estimates from the four reference colours in our analysis, we report in Fig. 6 the resulting  $T - \langle T \rangle$  distribution, considering the whole set of 322 individual residuals. The figure confirms that an unbiased estimate of  $T_{\text{eff}}$  may eventually be achieved with our procedure, within a  $\pm 150$  K uncertainty on the standard measure. As typically two to four useful temperature estimates are available from the colours of each star (see, again, Tables 11 and 12), we may expect final  $T_{\text{eff}}$  values for our sample to be assessed within a 70–100 K (i.e. 1–3 per cent) internal uncertainty.

#### 4.2 Towards $m_{\text{bol}}$

The fiducial effective temperature, as reported in column 10 of Tables 11 and 12, provided the reference quantity to constrain the unsampled fraction of stellar luminosity, outside the wavelength limits of our spectral observations. No univocal procedure can be devised to effectively tackle this problem. On one hand, in fact, both the ultraviolet and mid- and far-infrared stellar emission can in principle be modulated by a number of different mechanisms (mass loss and stellar winds, or circumstellar gas and dust lanes thermalizing ultraviolet and optical photons, photospheric spots, pulsating variability etc.). On the other hand, one would better like to proceed with a straight heuristic approach, such as to self-consistently size up the amount of ‘overflow’ luminosity and decide the accuracy level in its correction procedure, according to an ‘ex-post’ analysis of the results.

On this line, we therefore decided to proceed in the most straightforward way for each star, by extrapolating its observed SED to both ultraviolet and infrared windows by means of two black-body branches, of appropriate (fixed) temperature  $\langle T \rangle$  as given in Tables 11 and 12. The two spectral branches have been *separately* rescaled to the (dereddened) flux values of the observed SED by setting the boundary wavelengths respectively at 4000 and 22 500 Å; the integrated luminosity has then been computed within the three relevant regions of each stellar SED, identifying the



**Figure 5.** The resulting (dereddened) SED according to optical and infrared observations for an illustrative stellar subset of each cluster, including the brightest (and roughly coolest) and faintest (i.e. warmest) stars. Note, especially for the M15 stars, the strong impact of telluric water vapour bands at 1.38 and 1.88  $\mu\text{m}$ . Their variability along the observing nights prevented, in some cases, any accurate cleaning procedure. See discussion in Section 3.1.

ultraviolet contribution  $l_{\text{UV}}$  (in  $0 \leq \lambda \leq 4000 \text{ \AA}$ ) an optical/mid-infrared luminosity  $l_{\text{obs}}$  ( $4000 \leq \lambda \leq 22500 \text{ \AA}$ ) and a far-infrared contribution  $l_{\text{FIR}}$  (longward of  $2.25 \mu\text{m}$ ). For comparison, the same exercise has been repeated for a straight blackbody spectral distribution exploring the luminosity fraction emitted shortward of  $\lambda \leq 4000 \text{ \AA}$  and longward of  $\lambda \geq 22500 \text{ \AA}$  along the temperature range of our sample.

Our results are summarized in Fig. 7. Compared to the blackbody approximation, real stars are brighter at longer wavelength and slightly fainter, on the contrary, at UV wavelength. In total, one sees from Fig. 7 that the fraction of ‘lost’ luminosity, namely  $F_l = (l_{\text{bol}} - l_{\text{obs}})/l_{\text{bol}}$ , turns out to be about 15 per cent for the bulk of red giants in our sample; this figure can, however, quickly raise with decreasing temperature, and about one-third of bolometric luminosity might in fact be ‘stored’ at FIR wavelengths. Within these limits, and accounting for the 70–100 K internal uncertainty of our temperature scale, one sees from the Fig. 7 that  $m_{\text{bol}}$  can be secured for our sample stars within a few 0.01 mag uncertainty.<sup>7</sup>

Starting from the bolometric flux (which also includes the unsampled luminosity fraction, according to our procedure), the apparent magnitude for each star derives as  $m_{\text{bol}} = -2.5 \log f_{\text{bol}} + \text{Z.P.}$  If we assume for the Sun an absolute  $M_{\text{bol}} = +4.72$ , and  $L_{\odot} = 3.89 \cdot 10^{33} \text{ erg s}^{-1}$ , the bolometric zero-point directly derives as  $\text{Z.P.} = -11.50 \text{ mag}$ . On the same line, the BC scale is fixed once adopting an observed value for the apparent  $V$  magnitude of the Sun. Following Lang (1991), if  $m_V^{\odot} = -26.78$ , then  $M_V^{\odot} = +4.79$  and a  $\text{BC}_V^{\odot} = -0.07 \text{ mag}$  derives. Our output, for the whole stellar sample, is reported in column 11 of Tables 11 and 12, together with the relevant (dereddened) BC to the  $V$  and  $K$  photometric bands ( $\text{BC}_V$  and  $\text{BC}_K$ , respectively, in columns 12 and 13 of the tables).

## 5 RESULTS AND DISCUSSION

The data of Tables 11 and 12 are the main output of our analysis. According to our results, we can explore three relevant relationships, linking BC with the effective temperature of stars and with two reference colours like  $(B - V)$  and  $(V - K)$ . Given the temperature range of red giants, it could be of special relevance to consider the  $K$ -band BC; however, for its more general interest, we will also include in our discussion the more standard case of the  $\text{BC}_V$ .

### 5.1 BC-colour-temperature relations

Like, for a colour-colour diagram, the BC versus colour relationship can be regarded as an *intrinsic* (i.e. distance-independent) feature characterizing the stellar SED. On the corresponding theoretical side, we also want to study here the resulting dependence of BC on stellar effective temperature, a relation that allows us to more directly match the observations with the theoretical predictions of stellar model atmospheres.

In a first set of plots (see Fig. 8), we display the observed distribution of our stars in the different planes. In order to single out any possible dependence on chemical composition of stars, we marked

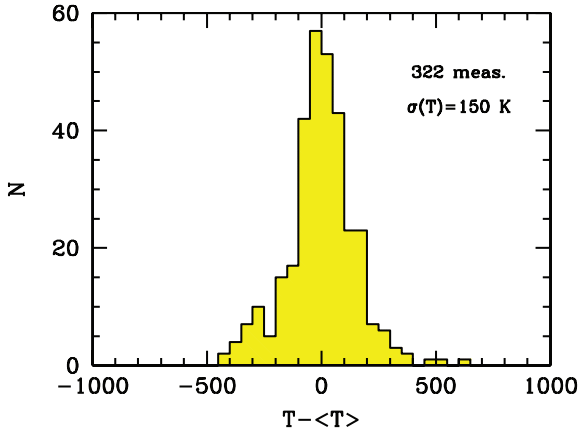
<sup>7</sup>The claimed  $m_{\text{bol}}$  uncertainty simply derives as  $\sigma \sim \partial F_l / \partial T_{\text{eff}} \sigma(T_{\text{eff}})$ , where  $\sigma(T_{\text{eff}}) \lesssim 100 \text{ K}$  and the  $F_l$  derivative can be estimated from Fig. 7. In any case, it is clear from the figure that, by neglecting any further luminosity correction to our data for the unsampled luminosity, we would be overestimating  $m_{\text{bol}}$  by at most 0.3 mag.

**Table 11.** Inferred temperatures, bolometric magnitude and bolometric corrections for target stars in globular clusters M71, M15 and M2.

| ID               | M15         |                 |             |             |                 |                 |                 |                 |                            |                  |                 |                 |
|------------------|-------------|-----------------|-------------|-------------|-----------------|-----------------|-----------------|-----------------|----------------------------|------------------|-----------------|-----------------|
|                  | $(B - V)_0$ | $(V - I_{C_0})$ | $(V - K)_0$ | $(J - K)_0$ | $T_{BV}$<br>(K) | $T_{VI}$<br>(K) | $T_{VK}$<br>(K) | $T_{JK}$<br>(K) | $\langle T \rangle$<br>(K) | Bol <sub>0</sub> | BC <sub>V</sub> | BC <sub>K</sub> |
| 21300002+1209182 | 0.71        | 0.87            | 2.08        | 0.58        | 5043            | 5039            | 5019            | 4748            | 4962                       | 13.742           | −0.25           | 1.83            |
| 21295705+1208531 | 0.85        | 1.01            | 2.34        | 0.62        | 4721            | 4711            | 4723            | 4619            | 4694                       | 12.697           | −0.34           | 1.99            |
| 21295532+1210327 | 0.81        | 1.03            | 2.44        | 0.73        | 4777            | 4669            | 4618            | 4307            | 4593                       | 13.754           | −0.37           | 2.07            |
| 21300090+1208571 | 1.04        | 1.27            | 3.13        | 0.96        | 4474            | 4242            | 4117            | 3806            | 4160                       | 11.918           | −0.67           | 2.45            |
| 21295473+1208592 | 0.99        | 1.09            | 2.58        | 0.62        | 4536            | 4549            | 4506            | 4619            | 4552                       | 13.032           | −0.46           | 2.12            |
| 21300461+1210327 | 1.06        | 1.07            | 2.60        | 0.83        | 4449            | 4588            | 4490            | 4068            | 4399                       | 13.148           | −0.39           | 2.20            |
| 21295560+1212422 | 1.03        | 1.07            | 2.64        | 0.81        | 4486            | 4588            | 4457            | 4113            | 4411                       | 12.733           | −0.42           | 2.22            |
| 21300514+1210041 | 0.79        | 0.92            | 2.40        | 0.76        | 4827            | 4915            | 4660            | 4231            | 4658                       | 13.674           | −0.33           | 2.07            |
| 21295836+1209020 | 0.87        | 1.02            | 2.55        | 0.75        | 4694            | 4690            | 4532            | 4256            | 4543                       | 13.102           | −0.42           | 2.13            |
| 21295618+1210179 | 1.03        | 1.25            | 3.07        | 0.89        | 4486            | 4272            | 4153            | 3941            | 4213                       | 11.934           | −0.65           | 2.42            |
| 21295739+1209056 | 0.96        | 1.09            | 2.53        | 0.57        | 4574            | 4549            | 4549            | 4782            | 4614                       | 13.068           | −0.45           | 2.07            |
| 21300097+1210375 | 0.96        | 1.06            | 2.44        | 0.66        | 4574            | 4608            | 4618            | 4499            | 4575                       | 13.135           | −0.41           | 2.03            |
| 21300431+1210561 | 1.07        | 1.18            | 2.67        | 0.70        | 4437            | 4386            | 4433            | 4387            | 4411                       | 12.798           | −0.48           | 2.18            |
| 21301049+1210061 | 0.99        | 1.11            | 2.74        | 0.85        | 4536            | 4511            | 4378            | 4024            | 4362                       | 12.586           | −0.46           | 2.27            |
| 21300739+1210330 | 1.07        | 1.22            | 2.68        | 0.71        | 4437            | 4320            | 4425            | 4360            | 4386                       | 13.252           | −0.49           | 2.19            |
| 21300569+1210156 | 0.81        | 0.98            | 2.34        | 0.66        | 4777            | 4776            | 4723            | 4499            | 4694                       | 13.472           | −0.33           | 2.01            |
| 21300553+1208553 | 0.88        | 1.07            | 2.92        | 0.80        | 4680            | 4588            | 4249            | 4136            | 4413                       | 14.012           | −0.52           | 2.40            |
| 21295756+1209438 | 1.25        | 1.28            | 2.86        | 0.73        | 4230            | 4227            | 4291            | 4307            | 4264                       | 11.556           | −0.58           | 2.27            |
| 21295082+1211301 | 0.99        | 1.09            | 2.59        | 0.69        | 4536            | 4549            | 4498            | 4414            | 4499                       | 12.778           | −0.43           | 2.15            |
| 21295716+1209175 | 0.83        | 1.03            | 2.56        | 0.73        | 4749            | 4669            | 4523            | 4307            | 4562                       | 12.303           | −0.42           | 2.14            |
| M2               |             |                 |             |             |                 |                 |                 |                 |                            |                  |                 |                 |
| 21333827−0054569 | 0.93        | 1.04            | 2.83        | 0.79        | 4640            | 4639            | 4312            | 4157            | 4437                       | 11.990           | −0.54           | 2.28            |
| 21333095−0052154 | 1.00        | 1.05            | 2.65        | 0.69        | 4540            | 4618            | 4447            | 4412            | 4504                       | 13.025           | −0.47           | 2.18            |
| 21332468−0044252 | 1.00        | 1.07            | 2.55        | 0.62        | 4540            | 4579            | 4530            | 4617            | 4566                       | 14.030           | −0.43           | 2.11            |
| 21331771−0047273 | 1.23        | 1.26            | 2.95        | 0.75        | 4251            | 4250            | 4230            | 4254            | 4246                       | 12.190           | −0.64           | 2.30            |
| 21331723−0048171 | 1.34        | 1.35            | 3.18        | 0.83        | 4110            | 4122            | 4090            | 4066            | 4097                       | 12.721           | −0.75           | 2.42            |
| 21331790−0048198 | 1.07        | 1.10            | 3.68        | 1.07        |                 | 4521            | 3912            | 3618            | 4017                       | 13.584           | −0.97           | 2.71            |
| 21331854−0051563 | 0.93        | 1.07            | 2.67        | 0.71        | 4640            | 4579            | 4431            | 4358            | 4502                       | 13.231           | −0.47           | 2.19            |
| 21331948−0051034 | 0.93        | 1.09            | 2.79        | 0.81        | 4640            | 4540            | 4340            | 4111            | 4408                       | 13.428           | −0.51           | 2.28            |
| 21331923−0049058 | 1.22        | 1.20            | 3.59        | 1.03        |                 | 4345            | 3950            | 3682            | 3992                       | 14.083           | −0.94           | 2.64            |
| 21332588−0046004 | 0.92        | 1.01            | 2.69        | 0.78        | 4655            | 4701            | 4416            | 4181            | 4488                       | 13.814           | −0.44           | 2.25            |
| 21333668−0051058 | 1.17        | 1.21            | 3.04        | 0.81        | 4314            | 4328            | 4173            | 4111            | 4232                       | 12.271           | −0.66           | 2.37            |
| 21333520−0046089 | 1.16        | 1.22            | 2.97        | 0.76        | 4326            | 4312            | 4217            | 4229            | 4271                       | 12.528           | −0.65           | 2.32            |
| 21333488−0047572 | 1.25        | 1.27            | 3.09        | 0.88        | 4215            | 4235            | 4143            | 3959            | 4138                       | 12.813           | −0.67           | 2.41            |
| 21333593−0049224 | 1.32        | 1.35            | 3.17        | 0.86        | 4133            | 4122            | 4096            | 4001            | 4088                       | 13.002           | −0.74           | 2.42            |
| 21333432−0051285 | 1.11        | 1.17            | 2.79        | 0.70        | 4391            | 4395            | 4340            | 4384            | 4378                       | 12.980           | −0.55           | 2.23            |
| 21332531−0052511 | 1.09        | 1.11            | 2.77        | 0.77        | 4417            | 4502            | 4355            | 4205            | 4370                       | 13.414           | −0.51           | 2.26            |
| 21333109−0054522 | 1.35        | 1.39            | 3.04        | 0.75        | 4098            | 4070            | 4173            | 4254            | 4149                       | 13.675           | −0.71           | 2.33            |
| 21333507−0051097 | 1.10        | 1.16            | 2.60        | 0.58        | 4404            | 4412            | 4488            | 4746            | 4512                       | 14.102           | −0.49           | 2.10            |
| M71              |             |                 |             |             |                 |                 |                 |                 |                            |                  |                 |                 |
| 19535325+1846471 | 1.39        | 1.54            | 3.75        | 0.86        |                 | 3908            | 3881            | 3999            | 3929                       | 10.455           | −1.14           | 2.61            |
| 19534750+1846169 | 1.11        | 1.12            | 2.85        | 0.71        | 4466            | 4496            | 4307            | 4355            | 4406                       | 11.760           | −0.57           | 2.28            |
| 19535150+1848059 | 1.41        | 1.54            | 3.61        | 0.95        |                 | 3908            | 3938            | 3821            | 3889                       | 10.522           | −1.02           | 2.59            |
| 19535064+1849075 | 1.18        | 1.20            | 3.08        | 0.89        | 4361            | 4356            | 4160            | 3937            | 4204                       | 11.577           | −0.67           | 2.42            |
| 19534575+1847547 | 1.47        | 1.65            | 3.77        | 0.97        |                 |                 | 3873            | 3784            | 3828                       | 10.554           | −1.15           | 2.62            |
| 19534827+1848021 | 1.42        | 1.49            | 3.58        | 1.02        |                 | 3961            | 3951            | 3697            | 3870                       | 10.606           | −0.98           | 2.60            |
| 19534656+1847441 | 0.96        | 1.02            | 2.47        | 0.62        | 4710            | 4694            | 4600            | 4614            | 4654                       | 12.438           | −0.42           | 2.06            |
| 19535369+1846039 | 0.70        | 0.74            | 2.00        | 0.58        | 5289            | 5410            | 5096            | 4742            | 5134                       | 13.556           | −0.21           | 1.79            |
| 19534905+1846003 | 1.02        | 1.04            | 2.61        | 0.63        | 4609            | 4653            | 4486            | 4583            | 4583                       | 12.209           | −0.47           | 2.15            |
| 19534916+1846512 | 0.96        | 0.95            | 2.66        | 0.76        | 4710            | 4849            | 4447            | 4227            | 4558                       | 12.434           | −0.44           | 2.22            |
| 19534178+1848384 | 0.96        | 0.98            | 2.46        | 0.71        | 4710            | 4781            | 4610            | 4355            | 4614                       | 13.405           | −0.37           | 2.09            |
| 19535676+1845399 | 0.90        | 0.92            | 2.38        | 0.66        | 4815            | 4920            | 4688            | 4494            | 4729                       | 13.379           | −0.35           | 2.04            |
| 19533962+1848569 | 0.78        | 0.80            | 2.27        | 0.63        | 5082            | 5234            | 4800            | 4583            | 4925                       | 13.636           | −0.29           | 1.98            |
| 19533864+1847554 | 1.03        | 0.98            | 2.32        | 0.50        | 4593            | 4781            | 4748            | 5029            | 4788                       | 12.980           | −0.34           | 1.98            |
| 19534615+1847261 | 1.21        | 1.26            | 3.08        | 0.78        | 4318            | 4260            | 4160            | 4178            | 4229                       | 11.728           | −0.71           | 2.38            |
| 19534941+1844269 | 1.60        | 2.20            | 4.37        | 0.87        |                 |                 | 3676            | 3978            | 3827                       | 9.541            | −1.70           | 2.67            |

**Table 12.** Inferred temperatures, bolometric magnitude and bolometric corrections for target stars in open clusters NGC 188 and NGC 6791.

| ID               | NGC 188     |               |             |             |                 |                 |                 |                 |                            |                  |                 |                 |
|------------------|-------------|---------------|-------------|-------------|-----------------|-----------------|-----------------|-----------------|----------------------------|------------------|-----------------|-----------------|
|                  | $(B - V)_0$ | $(V - I_C)_0$ | $(V - K)_0$ | $(J - K)_0$ | $T_{BV}$<br>(K) | $T_{VI}$<br>(K) | $T_{VK}$<br>(K) | $T_{JK}$<br>(K) | $\langle T \rangle$<br>(K) | Bol <sub>0</sub> | BC <sub>V</sub> | BC <sub>K</sub> |
| 00445253+851405  | 1.22        | 1.20          | 2.66        | 0.55        | 4398            | 4354            | 4470            | 4854            | 4519                       | 11.552           | −0.53           | 2.13            |
| 00475922+851132  | 1.46        | 1.27          | 2.65        | 0.49        | 4040            | 4243            | 4478            | 5078            | 4460                       | 11.311           | −0.56           | 2.09            |
| 00465966+851315  | 1.38        | 1.16          | 2.50        | 0.54        | 4153            | 4422            | 4602            | 4889            | 4516                       | 11.701           | −0.44           | 2.06            |
| 00554526+851220  | 1.34        | 1.35          | 3.05        | 0.73        | 4211            | 4129            | 4201            | 4309            | 4212                       | 9.842            | −0.72           | 2.33            |
| 00463920+852333  | 1.24        | 1.22          | 2.83        | 0.65        | 4366            | 4321            | 4344            | 4530            | 4390                       | 10.706           | −0.60           | 2.23            |
| 00472975+852414  | 1.05        | 1.04          | 2.70        | 0.68        | 4695            | 4650            | 4439            | 4444            | 4557                       | 12.166           | −0.49           | 2.21            |
| 00441241+850931  | 1.44        | 1.47          | 3.27        | 0.78        | 4068            | 3981            | 4078            | 4184            | 4078                       | 10.165           | −0.86           | 2.41            |
| 00432696+850917  | 0.94        | 0.93          | 2.32        | 0.62        | 4909            | 4893            | 4772            | 4621            | 4799                       | 12.578           | −0.31           | 2.02            |
| 00490560+852607  | 1.15        | 1.11          | 2.45        | 0.47        | 4516            | 4513            | 4646            | 5159            | 4708                       | 11.945           | −0.45           | 2.00            |
| 00420323+852049  | 1.45        | 1.48          | 3.32        | 0.81        | 4054            | 3970            | 4052            | 4114            | 4048                       | 8.628            | −0.87           | 2.46            |
| ID               | NGC 6791    |               |             |             |                 |                 |                 |                 |                            |                  |                 |                 |
|                  | $(B - V)_0$ | $(V - I_C)_0$ | $(V - K)_0$ | $(J - K)_0$ | $T_{BV}$<br>(K) | $T_{VI}$<br>(K) | $T_{VK}$<br>(K) | $T_{JK}$<br>(K) | $\langle T \rangle$<br>(K) | Bol <sub>0</sub> | BC <sub>V</sub> | BC <sub>K</sub> |
| 19210807+3747494 | 1.19        | 1.09          | 2.79        | 0.73        | 4554            | 4544            | 4397            | 4304            | 4450                       | 13.100           | −0.52           | 2.27            |
| 19205259+3744281 | 1.47        | 1.59          | 3.58        | 0.91        |                 | 3844            | 3953            | 3898            | 3898                       | 12.720           | −1.02           | 2.56            |
| 19205580+3742307 | 1.21        | 1.12          | 2.62        | 0.59        | 4518            | 4488            | 4527            | 4712            | 4561                       | 14.053           | −0.48           | 2.13            |
| 19205671+3743074 | 1.21        | 1.14          | 2.66        | 0.60        | 4518            | 4451            | 4495            | 4679            | 4536                       | 13.773           | −0.50           | 2.15            |
| 19210112+3742134 | 1.34        | 1.37          | 3.20        | 0.80        | 4294            | 4098            | 4138            | 4133            | 4166                       | 13.322           | −0.80           | 2.40            |
| 19211606+3746462 | 1.43        | 3.10          | 5.58        | 1.01        |                 |                 | 3418            | 3715            | 3566                       | 10.646           | −2.73           | 2.85            |
| 19213656+3740376 | 1.39        | 1.42          | 3.25        | 0.84        | 4214            | 4035            | 4111            | 4043            | 4101                       | 12.902           | −0.81           | 2.44            |
| 19210326+3741190 | 1.21        | 1.19          | 2.71        | 0.61        | 4518            | 4365            | 4456            | 4647            | 4496                       | 13.493           | −0.53           | 2.17            |
| 19213635+3739445 | 1.22        | 1.08          | 2.86        | 0.83        | 4499            | 4563            | 4348            | 4065            | 4369                       | 13.867           | −0.53           | 2.33            |
| 19212437+3735402 | 1.25        | 1.12          | 2.84        | 0.78        | 4446            | 4488            | 4361            | 4180            | 4369                       | 13.561           | −0.54           | 2.30            |
| 19212674+3735186 | 1.23        | 1.23          | 2.87        | 0.73        | 4482            | 4299            | 4341            | 4279            | 4350                       | 13.034           | −0.58           | 2.29            |
| 19211632+3752154 | 1.12        | 1.12          | 2.73        | 0.72        | 4686            | 4488            | 4441            | 4330            | 4486                       | 13.119           | −0.50           | 2.23            |
| 19211176+3752459 | 1.15        | 1.08          | 2.65        | 0.66        | 4629            | 4563            | 4503            | 4496            | 4548                       | 13.538           | −0.48           | 2.17            |
| 19202345+3754578 | 1.65        | 2.98          | 5.64        | 1.06        |                 |                 | 3407            | 3633            | 3520                       | 9.718            | −2.72           | 2.92            |
| 19205149+3739334 | 1.48        | 2.72          | 5.11        | 1.06        |                 |                 | 3504            | 3633            | 3568                       | 9.043            | −2.25           | 2.85            |
| 19203285+3753488 | 1.46        | 3.20          | 5.88        | 1.21        |                 |                 | 3368            | 3416            | 3392                       | 10.107           | −2.92           | 2.96            |
| 19200641+3744452 | 1.21        | 1.26          | 3.15        | 0.86        | 4518            | 4253            | 4166            | 4000            | 4234                       | 12.259           | −0.72           | 2.43            |
| 19200882+3744317 | 1.43        | 3.76          | 6.58        | 1.14        |                 |                 | 3260            | 3512            | 3386                       | 9.664            | −3.59           | 2.99            |
| 19203219+3744208 | 1.33        | 4.35          | 7.52        | 1.19        |                 |                 | 3120            | 3443            | 3282                       | 9.934            | −4.47           | 3.05            |



**Figure 6.** Histogram of temperature difference for all the data reported in Tables 8 and 9 (columns 6–9) with respect to the adopted mean estimate ( $\langle T \rangle$  of column 10). A total of 322 entries are available for the whole stellar sample. The resulting distribution gives a direct measure of the internal uncertainty of our temperature scale, amounting to  $\sigma(T_{\text{eff}}) = \pm 150$  K for the standard individual estimate.

metal-poor ( $[\text{Fe}/\text{H}] < -1.0$  dex, dots) and metal-rich ( $[\text{Fe}/\text{H}] > -1.0$  dex, triangles) objects differently. For better convenience in our study, we also fitted the overall distribution analytically; a useful set of fitting functions for the BC versus  $T_{\text{eff}}$  relations along the

$3300 \lesssim T_{\text{eff}} \lesssim 5000$  K temperature range results in the following:

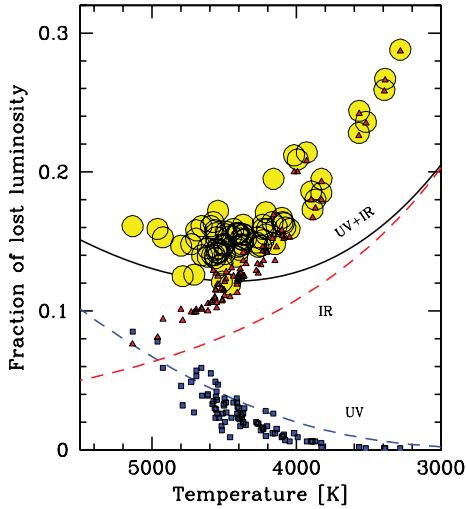
$$\begin{cases} \text{BC}_V = -\exp(27\,500/T_{\text{eff}})/1000 \\ (\sigma_{\text{BC}}, \rho) = (0.11, 0.989), \\ \text{BC}_K = -6.75 \log(T_{\text{eff}}/9500) \\ (\sigma_{\text{BC}}, \rho) = (0.05, 0.978). \end{cases} \quad (4)$$

As for the colour relations, the non-monotonic trend of  $\text{BC}_V$  versus  $(B - V)$  (see upper left-hand panel in Fig. 8) prevents us to use the colour as an independent (i.e. ‘input’) variable in our fit. In this case we had therefore to adjust an inverse relation, assuming BC as the running variable. The corresponding set of analytical solutions, along the same temperature range as that in the previous equation set, eventually results in the following:

$$\begin{cases} B - V = 1.906 [\text{BC}_V^2 \exp(\text{BC}_V)]^{0.3} \\ (\sigma_{BV}, \rho) = (0.11, 0.863), \\ V - K = 1/(1 - 0.283 \text{BC}_K) \\ (\sigma_{VK}, \rho) = (0.13, 0.991). \end{cases} \quad (5)$$

All these fits are superposed to the data of Fig. 8 as a solid line.

Just on the basis of our data note how difficult it is to firmly constrain the  $(B - V)$  versus  $\text{BC}_V$  behaviour at very low temperature. On one hand, in fact, the intervening effect of the TiO absorption at visual wavelength (Kučinskas et al. 2005) makes the  $(B - V)$



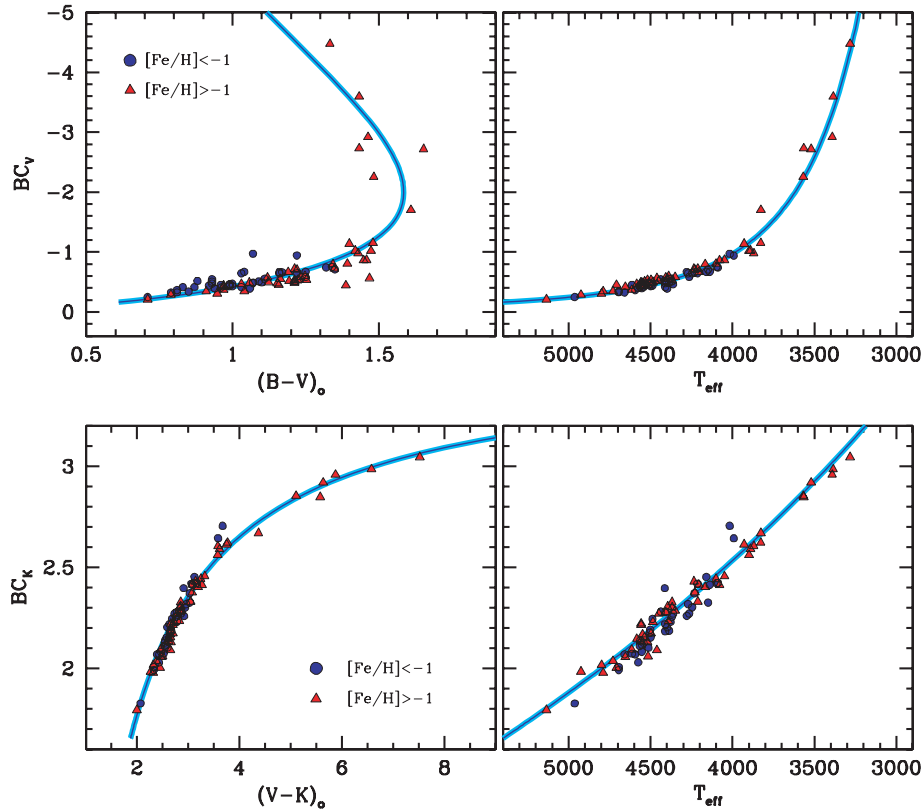
**Figure 7.** Estimated fraction of unsampled stellar luminosity for the stars in our sample (big solid dots). The relative contribution to stellar bolometric luminosity from lost emission at short (i.e. for  $\lambda \leq 4000 \text{ \AA}$ , small square markers on the plot) and long (i.e. for  $\lambda \geq 2.25 \mu\text{m}$ , small triangles) wavelength is sized up by extrapolating the observed SED with two blackbody (BB) ‘wings’ at fixed  $\langle T \rangle$ , as from column 10 of both Tables 11 and 12. The same exercise is carried out for a full BB spectrum along the 5500–3000 K temperature range (dashed lines labelled ‘UV’ and ‘IR’ for the short and long wavelength contribution, respectively, together with their summed contribution, as in the solid line). Compared to a plain BB case, note that real stars at cool temperatures display a brighter IR luminosity.

colour of stars that are cooler than  $\sim 3700 \text{ K}$  saturate strongly, reaching a maximum of about  $(B - V)_{\text{max}} \simeq 1.5$  and turning back to bluer values for later M-type stars. On the other hand, the apparent trend in our sample in this range is evidently biased by the NGC 6791 stellar population with just a few super-metal-rich giants constraining the  $BC_V$  trend at the most extreme negative values.

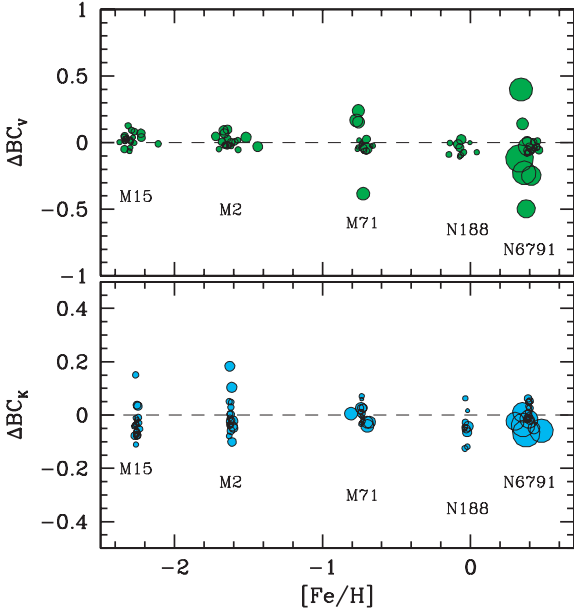
## 5.2 BC response to metallicity

As a part of our observing strategy, the sampled stellar population of the five clusters would in principle allow one to better single out any possible dependence of BC on stellar chemical composition. As far as helium content is concerned, for instance, this problem has already been tackled by Girardi et al. (2007) through a series of theoretical models based on the Kurucz (1992) ATLAS9 model atmospheres. As a main result of their discussion, these authors did not find any relevant impact on stellar BC to optical photometric bands when helium changes up to  $\Delta Y = +0.2$ , for fixed effective temperature. To some extent, this is a not-so-surprising behaviour; helium is in fact a substantial contributor to mean particle weight of stellar plasma but a negligible contributor to chemical opacity. Accordingly, with varying  $Y$  in the chemical mix, one has to expect a much more explicit impact on stellar temperature for fixed mass of stars, rather than on colours or SED for fixed effective temperature (as explored by Girardi et al. 2007 models, indeed).

The situation might in principle be different for the metals, mainly through their pervasive effect on stellar blanketing at short wavelength. In addition, metals are the basic ingredients required to



**Figure 8.** The BC versus colour (left-hand panels) and BC versus  $T_{\text{eff}}$  (right-hand panels) distribution of our stellar sample (dots and triangles, for metal-poor and metal-rich stars, respectively). Synthetic colours have been corrected for Galactic reddening. Solid lines are our derived calibrations, according to the set of equations (4) and (5).



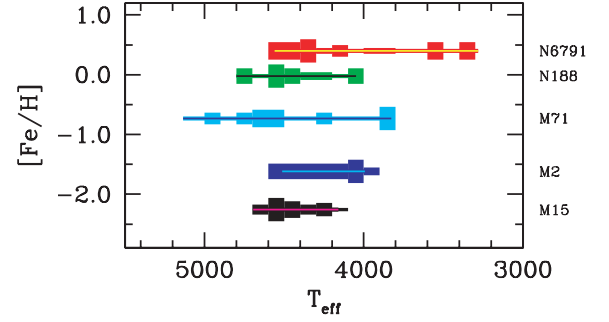
**Figure 9.** The distribution of BC residuals for our stellar sample versus cluster metallicity. The displayed  $\Delta BC$  is intended as the difference between the values of columns 12 and 13 of both Tables 11 and 12 and the output of equation (4) entering along with the adopted effective temperature of stars, as in column 10 of the tables. Note the lack of any evident correlation with  $[Fe/H]$ , as discussed in more detail in Section 5.2. Data in the plot have been slightly spread around the cluster  $[Fe/H]$  value for better reading. Dot size is inversely proportional to star temperature (i.e. bigger dots = cooler red giants).

produce molecules like  $TiO$ ,  $SiH$  or  $CH$ , whose impact may be extremely relevant at blue and visual wavelength, when effective temperature lowers below 3500 K (Kučinskas et al. 2005; Bertone et al. 2008).

Taking the results of Tables 11 and 12 as a reference, in Fig. 9 we plot the BC residual distribution computed as a difference between the inferred BC (columns 12 and 13 in the tables) and the ‘mean’ locus of equation (4), once entering the equations with the fiducial  $\langle T \rangle$  of column 10. The BC residuals are displayed along the  $[Fe/H]$  distribution of the five star clusters, as labelled on the plots. Just a glance to both panels of the figure makes evident the lack of any drift of BC with stellar metallicity. Within the accuracy limits of our analysis, this means that two red giant stars of the same effective temperature but different  $[Fe/H]$  have virtually indistinguishable values of BC to V and K bands.

On the other hand, to correctly understand our conclusion, one has to pay attention to the different temperature regimes that mark spectral properties of red giant stars. In fact, stars warmer than  $\sim 4000$  K may have their SED depressed at short wavelength mostly in force of *atomic* transitions of Fe and other metals; on the contrary, for a cooler temperature, the metal opacity mainly acts in the form of *molecular* absorptions, making the broad-band systems the prevailing features that modulate the stellar SED. As a consequence, while for stars of spectral type G or earlier any change of  $Z$  simply implies a change in the blanketing strength, this may not straightforwardly be the case for later spectral types, where molecules play a much more entangled role with changing  $T_{\text{eff}}$ .

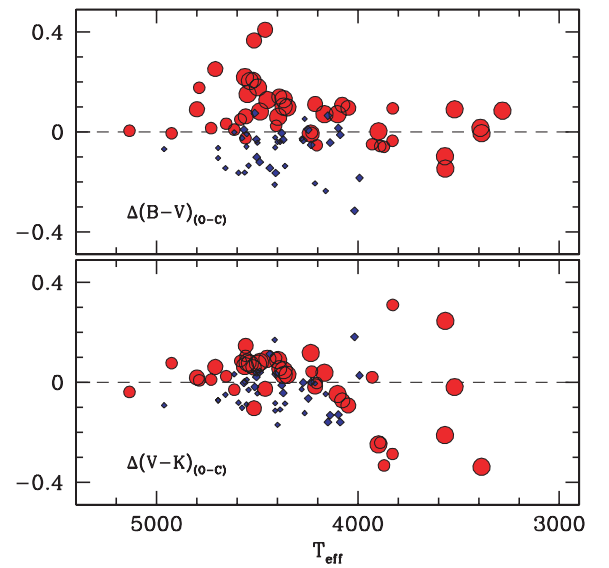
In order to better quantify the terms of our analysis, in this respect, we display in Fig. 10 the temperature distribution of stars in our sample across the metallicity range spanned by the five clusters considered. As a striking feature, note that only for NGC 6791 we



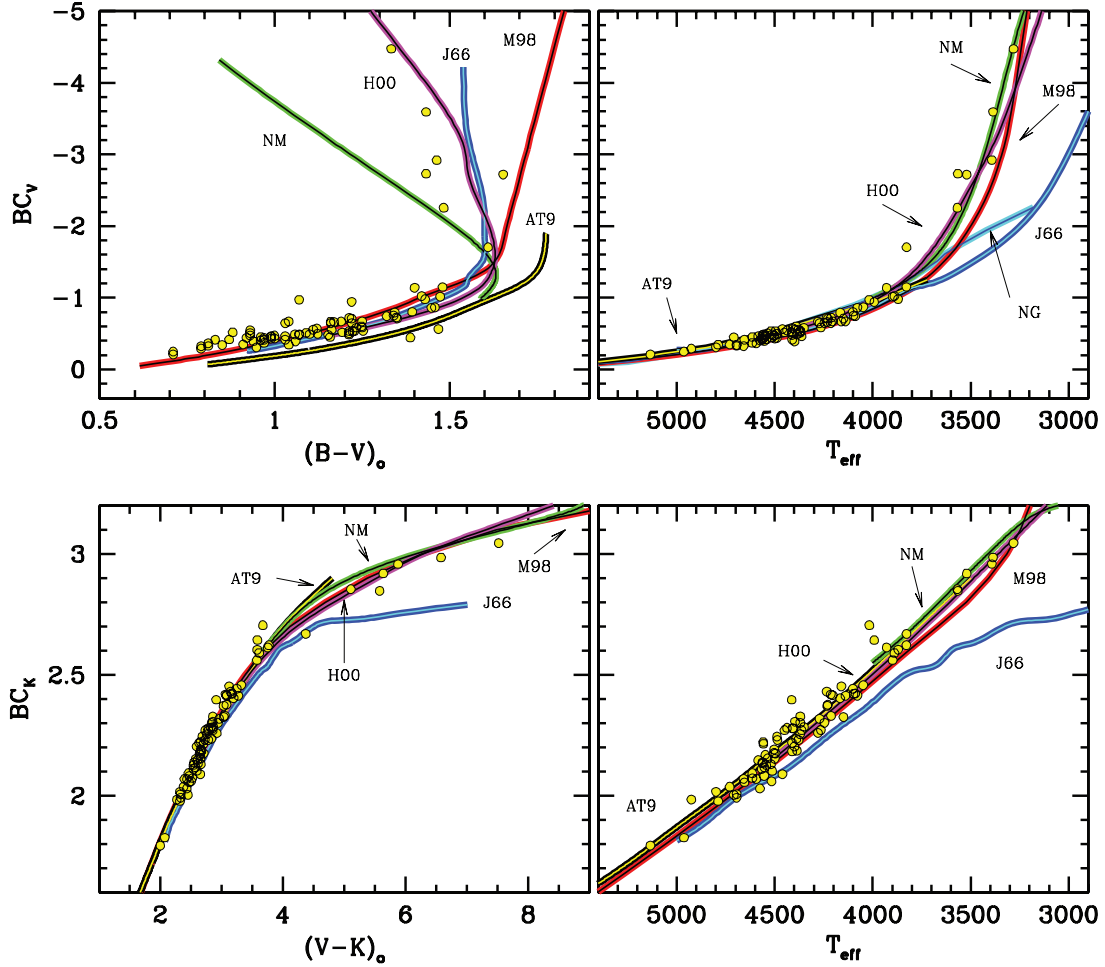
**Figure 10.** Temperature distribution of red giant stars in each of the five clusters of our sample, according to Tables 11 and 12. Line thickness is proportional to the star density along the spanned temperature range. Note that only cluster NGC 6791 contains stars cooler than  $\sim 3800$  K.

are able to probe stars cooler than  $\sim 3800$  K. The obvious *caveat* in our discussion is therefore that we can only assess the impact of *atomic* blanketing on stellar BC, while no firm conclusions can be drawn for the BC dependence on molecular absorption, facing the evident bias of our star sample against cool ( $T_{\text{eff}} \ll 4000$ ) objects.

As far as the blanketing is the prevailing mechanism at work in G–K stars, the basic physics of stellar atmospheres leads one to conclude that the V-band (and even more the K-band) luminosity is nearly unaffected by metal absorption, so that BC cannot vary much with  $[Fe/H]$ . Rather,  $B$  (and even more  $U$ ) magnitudes must be more strongly modulated by metal abundance making  $BC_B$  (and  $BC_U$ ) more directly sensitive to  $[Fe/H]$ . On the other hand, as  $BC_B = BC_V - (B - V)$ , one can straightaway ‘translate’ this metallicity effect in terms of apparent  $(B - V)$  colour change. This is shown in Fig. 11, where, for each star in our sample, we have computed the residual  $(B - V)$  and  $(V - K)$  colour as a difference between observed and expected values by entering in equation (5) the fitted value of BC as from equation (4). Metallicity is traced



**Figure 11.** Residual  $(B - V)$  and  $(V - K)$  distribution versus stellar temperature for stars in Tables 11 and 12. Colour residual is computed as a difference between observed and expected values by entering equation (5) along with the BC output of equation (4). Metal-poor and metal-rich stars are singled out by diamonds and dot markers, respectively, taking the value  $[Fe/H] = -1.0$  dex as a reference threshold. Marker size increases with  $[Fe/H]$ , throughout.



**Figure 12.** Same as Fig. 8, but comparing our data with different theoretical and empirical calibrations from Johnson (1966, ‘J66’ labels), Bertone et al. (2004) using ATLAS9 (Kurucz 1992, ‘AT9’) and NEXTGEN (Hauschildt et al. 1999, ‘NG’) synthesis codes for model atmosphere computation, Montegriffo et al. (1998, ‘M98’) and Houdashelt et al. (2000, ‘H00’) using MARCS theoretical code by Bell & Gustafsson (1978), and its updated version (NMARCS), as in Plez et al. (1992) and Bessell et al. (1998, ‘NM’).

in the plot by the marker size (the bigger the marker the higher the  $[\text{Fe}/\text{H}]$  value); again, we discriminate between metal-poor (diamonds) and metal-rich (dots) stars, taking the value  $[\text{Fe}/\text{H}] = -1.0$  dex as a reference threshold.

A trend of  $\Delta(B - V)$  versus cluster metallicity is now clearly evident, with the metal-poor and metal-rich star samples neatly segregated in the plot, the latter stars displaying a ‘redder’  $(B - V)$  colour (and correspondingly a positive colour residual) for fixed effective temperature. On the contrary, note that both ‘metal-poor’ and ‘metal-rich’ stars are well mixed in the  $\Delta(V - K)$  plot, witnessing once more the property of the  $V - K$  colour as a virtually metal-independent feature.

Considering in more detail the  $\Delta(B - V)$  distribution versus cluster metallicity, a fit to the data provides the following:<sup>8</sup>

$$-\Delta\text{BC}_B \equiv \Delta(B - V) = 0.10 [\text{Fe}/\text{H}] \pm 0.13 \pm 1 \pm 2 \quad (6)$$

with error bars at  $1\sigma$  level and  $(\text{rms}, \rho) = (0.09 \text{ mag}, 0.70)$ .

<sup>8</sup>Of course, following our previous arguments, we had to exclude from our analysis cluster NGC 6791, for its obvious bias in constraining the empirical  $T_{\text{eff}}$  versus  $(B - V)$  relationship for stars at supersolar metallicity.

### 5.3 Comparison with other BC scales

For a better understanding of our results, it is relevant to compare our output with other popular calibration scales often taken as a reference in the current literature and especially to attempt to extend their analysis to cool ( $T_{\text{eff}} \lesssim 3500 \text{ K}$ ) stellar temperatures. In particular, we will focus here on different theoretical BC calibrations relying on the three leading codes for advanced computation of stellar model atmospheres, namely ATLAS9 (Kurucz 1992, hereafter labelled as ‘AT9’), NEXTGEN (Hauschildt, Allard & Baron 1999, ‘NG’), both as reported by Bertone et al. (2004), and MARCS (Bell & Gustafsson 1978, as adopted by Houdashelt et al. 2000, ‘H00’ label) also in its updated versions (NMARCS, as in Plez, Brett & Nordlund 1992; Bessell et al. 1998, ‘NM’).

We will also consider in our analysis two empirical studies, i.e. the ones of Johnson (1966, referred to as ‘J66’) and Montegriffo et al. (1998, labelled as ‘M98’), both based on a careful analysis of infrared colours to assess the problem of the bolometric correction and a self-consistent temperature scale for red giant stars. All the bolometric scales in the figure have been shifted such as to agree with our assumption that  $\text{BC}_V^{\odot} = -0.07 \text{ mag}$ .

A synoptic look of the different theoretical and empirical frameworks is eased by the four panels of Fig. 12, where we report the

$BC_V$  and  $BC_K$  scales versus observables [i.e.  $(B - V)$  and  $(V - K)$  colours, respectively] and theoretical ( $T_{\text{eff}}$ ) reference quantities. In all respects, this figure is fully equivalent to, and can be compared to, Fig. 8, where we have reported our own results.

Just a quick look to the different curves of Fig. 12 gives an immediate picture of the inherent uncertainties in predicted BC according to the different calibration scales. The big issue, in this regard, much deals with the way models can reproduce cool stars and observations can account for the  $(B - V)$  ‘saturation’ versus temperature consequent to the shifted emission towards longer wavebands when stars become cooler than 3500 K. This effect makes the  $B$ -luminosity contribution to drop to nominal values among red giants, and the increasingly important role of molecular absorption strongly modulates optical colours of K- and M-type stars.

The still inadequate theoretical performance in modelling such cool stars with convenient accuracy fatally frustrates also any empirical effort to derive a firm temperature scale and an accurate abundance analysis for stars at the extreme edge of the temperature distribution (see e.g. Bertone et al. 2008 and Olling et al. 2009, for useful considerations on this subject).

As far as the  $BC_V$  versus  $(B - V)$  behaviour is concerned, the reference calibrations display the largest spread, with M98 predicting increasingly redder stars with decreasing temperature. On the opposite, NM predicts a sharp colour ‘turnback’, with  $BC_V$  increasing in absolute value among cool stars getting bluer and bluer. Definitely, the empirical calibration by J66 still remains a reference one, tracking the observations fairly well. This trend is also replied very closely by the MARCS models by H00, that provide an even better match to the data and a substantial agreement with our fitting function as in Fig. 8.

On conversion of colours to the theoretical plane of effective temperature (upper right-hand panel of Fig. 12), the picture slightly changes, in particular with a striking discrepancy of the J66 and the theoretical NG temperature scale for  $T_{\text{eff}} \lesssim 3800$  K. Both sources predict, in fact, much shallower corrections for cool stars than we observe. An overall agreement has to be reported, on the contrary, among the other calibrations, all replying our equation (4).

The situation is much eased in the infrared domain, where a monotonic relationship between  $(V - K)$  colour and  $BC_K$  characterizes red giant stars. In this new framework, both the theoretical and empirical planes are well reproduced by the different calibration scales, with the only remarkable exception of J66 that, to some extent ‘allows’ stars to store a bigger fraction of their bolometric luminosity in the infrared. This leads to a tipping  $BC_K \simeq 2.7$  and a too ‘red’  $(V - K)$  for a given value of  $T_{\text{eff}}$ .

Combining the different pieces of information coming from these comparisons, it seems that the H00 MARCS models are by far the best ones in matching our BC estimates, closely replying in every panel of Fig. 12 our empirical fitting functions of equations (4) and (5) and Fig. 8. In spite of this comforting appearance, however, this conclusion may be even more puzzling from a physical point of view, as the H00 models have been a fortiori tuned up such as to reproduce the observed colours of M stars. As described by the authors, this is required in particular to strongly enhance the assumed TiO opacities well beyond the admitted physical range suggested by molecular theory and implemented in the ‘standard’ MARCS library (Gustafsson et al. 2008).

## 6 SUMMARY AND CONCLUSIONS

A firm knowledge of a fully reliable link between observations and stellar evolution models is a basic, crucial requirement for any safe

use of stellar clocks and population synthesis templates in the study and interpretation of the integrated spectrophotometric properties of distant galaxies. Actually, the ‘stellar path’ to cosmology is strictly dependent, among others, on the accurate determination of the bolometric emission of stars, with varying effective temperatures and chemical abundance.

In this framework, we have tackled the central question of the possible BC dependence on stellar metallicity by securing spectroscopic observations for a wide sample of 92 red giant stars in five (three globular + two open) Galactic clusters along the full metallicity range from  $[\text{Fe}/\text{H}] = -2.2$  up to  $+0.4$  (see Section 3). The spectra cover the wavelength range from 3500 Å to 2.5 µm, collecting optical and IR observations. As a delicate task for the final settlement of our stellar data base, we dealt with the accurate flux calibration and a consistent match of the optical and near-IR sides of the spectra such as to reproduce, for each star, the broad-band  $BVR_C I_C JHK$  photometry available in the literature (Sections 2 and 3). Overall, we are confident that stellar SED along the entire sampled wavelength range was set up within a  $\pm 10$  per cent internal accuracy (see Table 7 and Fig. 3).

According to our previous arguments, however, one has also to carefully account for the lost contribution of ultraviolet and far-IR luminosity to the bolometric flux, depending on the effective temperature of stars. Based on the Alonso et al. (1999)  $T_{\text{eff}}$ -colour fitting functions, we took the four colours  $(B - V)$ ,  $(J - K)$ ,  $(V - I_C)$  and  $(V - K)$  as a reference for our calibration, leading to the constraining of  $T_{\text{eff}}$  for each stars in our sample within an estimated error better than  $\pm 100$  K (see Section 4.1), along the whole spanned temperature range ( $3300 \leq T_{\text{eff}} \leq 5000$  K).

The fiducial temperature allowed us to shape the unsampled portion of the SED at UV and far-IR wavelength by assuming a blackbody emission independently rescaled such as to connect the short- and long-wavelength edge of the observed spectra. As shown in Section 4.2 (see also Fig. 7), under the blackbody assumption, the internal uncertainty in our temperature scale only impact by a few 0.01 mag uncertainty in the inferred bolometric magnitude of our stars. In any case, by fully neglecting any unsampled spectral contribution, our data would be overestimating  $M_{\text{bol}}$  by at most 0.3 mag.

Making use of our new data base, we have been able to draw a convenient set of fitting functions for the BC versus  $T_{\text{eff}}$ , valid over the interval  $3300 \leq T_{\text{eff}} \leq 5000$  K (see Section 5.1, equation 4). Similar relationships for BC versus stellar colours cannot be straightforwardly derived (equation 5), especially for the  $(B - V)$ , which shows a strong saturation effect for stars cooler than 3700 K, in consequence of the intervening TiO absorption at visual wavelength (Kučinskas et al. 2005). In assessing properties of such very cool stars, however, one has also to consider that our sample is strongly biased against high-metallicity values as only the red giant branch of NGC 6791 ( $[\text{Fe}/\text{H}] = +0.4$ ) hosts stars with  $T_{\text{eff}} < 3700$  K.

Thanks to the wide  $[\text{Fe}/\text{H}]$  range spanned by G stars in the five clusters considered here, we explored the possible BC dependence on stellar metallicity. As far as atomic transitions prevail as the main source of metal opacity in the spectra of relatively warm ( $T_{\text{eff}} \gtrsim 4000$  K) stars, our data confirm that no evident trend of BC with  $[\text{Fe}/\text{H}]$  is in place (see Fig. 9). In other words, two red giant stars of the same effective temperature but different  $[\text{Fe}/\text{H}]$  are virtually indistinguishable in the values of BC to  $V$  and  $K$  bands. Things may be different, however, for the  $B$  (and even more for  $U$ ) magnitudes, where the blanketing effects are more and more severe. In fact, Fig. 11 clearly shows that metal-poor stars display a ‘bluer’  $(B - V)$  compared to corresponding metal-rich objects with the same

$T_{\text{eff}}$ . This leads us to conclude that a drift may be expected for  $BC_B$  such as  $BC_B \propto -0.10 [\text{Fe}/\text{H}]$  among stars with fixed value of  $T_{\text{eff}}$ .

To consistently verify our calibrations, we have shown in Fig. 12 plots of  $BC_V$  and  $BC_K$  versus colours and  $T_{\text{eff}}$ , respectively, by comparing with different theoretical and empirical calibrations currently available in the literature. As far as theoretical predictions are concerned, it seems that the H00 models are the best ones matching our data in every relationship. This feature is not a surprising one, however, given the recognized intention of the H00 calculations to match M stars via ad hoc tuning of molecular opacity. Actually, this successful comparison may add a further piece of evidence, all the way, to the persisting limitation of theory to independently assess the modelling of cool stars.

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