Bolometric correction and spectral energy distribution of cool stars in Galactic clusters

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ABSTRACT

In this work 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 Å → 2.5 \( \mu \)m wavelength range, for a grid of 92 red giant stars in five (3 globular + 2 open) Galactic clusters, along the full metallicity range covered by the bulk of the stars, −2.2 \( \lesssim [Fe/H] \lesssim +0.4 \).

Synthetic \( BV R_c I_c JHK \) photometry from the derived spectral energy distributions allowed us to obtain robust temperature (\( T_{\text{eff}} \)) estimates for each star, within ±100 K or less. According to the appropriate temperature estimate, black-body extrapolation of the observed spectral energy distribution (SED) 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% of the total bolometric luminosity, a figure that raises up to 30% for the coolest targets (\( T_{\text{eff}} \lesssim 3500 \) K). Allover, we trust to infer stellar \( M_{\text{bol}} \) values with an internal accuracy of a few percent. Even neglecting any correction for lost luminosity etc. we would be overestimating \( M_{\text{bol}} \) by \( \lesssim 0.3 \) mag, in the worst cases. Making use of our new database, we provide a set of fitting functions for the V and K BC vs. \( T_{\text{eff}} \) and vs. \( (B-V) \) and \( (V-K) \) broad-band colors, valid over the interval 3300 K \( \leq T_{\text{eff}} \leq 5000 \) K, especially suited for Red Giants.

The analysis of the BC\textsubscript{V} and BC\textsubscript{K} estimates along the wide range of metallicity spanned by our stellar sample show no evident drift with \([Fe/H]\). Things may be different for the B-band correction, where the blanketing effects are more and more severe. A drift of \( \Delta (B-V) \) vs. \([Fe/H]\) 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 color/temperature range considered in this paper, and (b) the same conclusion apply to \( BC_V \) only for stars warmer than \( \simeq 3800 \) 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 \( BC_V \) vs. \( (B-V) \) plane.

Key words: Stars: late-type – Stars: atmospheres – Galaxy: 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 observations 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 of a star, then we could physically “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 well known, however, \( L \) cannot, in principle, be directly measured, requiring for this task an ideal detector equally sensitive to the whole spectral range. 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.\(^1\) Relying on this approach, Johnson (1966) derived the bolometric vs. temperature scale for red giant stars, while Code et al. (1976) explored the same relation for hot early-type stars, through satellite-borne UV observations. As an alternative way, many authors tried a fully theoretical assessment of the problem, by studying the \( f_{\text{bol}} \) vs. \( f_{\lambda} \) relationship on the basis of model grids of stellar atmospheres and replacing observations with synthetic photometry directly computed on the theoretical SED (Bertone et al. 2004; Bessell, Castelli, & Plez 1998).

Rather than focusing 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 extensively applied to the study of giant and supergiant stars (Blackwell, Shallis, & Selby 1976; di Benedetto & Rabbi 1987; Blackwell & Lynam-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. \( \mu = (f_{\text{bol}}/f_{\text{IR}})_{\text{IR}} \).

Although in different forms, all the previous methods used theoretical models of stellar atmospheres to derive the appropriate “correcting factor” \( R = f_{\text{bol}}/f(\lambda) \) and convert observed or synthetic monochromatic magnitudes, \( m(\lambda) \) to the bolometric scale.\(^2\) Taking the Sun as a reference source for our calibration, we could write more explicitly:

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

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

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

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 eq. (2) makes clear some important properties of \( BC \): i) the value of \( R \) is a composite function of stellar fundamental parameters, namely \( R = R(T_{\text{eff}}, \log g, [X/H]) \) so that, for fixed effective temperature, \( BC \) may display some dependence on stellar gravity \( (g) \) and chemical composition \((X/H)\); ii) the value of \( R \) (and, accordingly, of \( BC \)) is minimum when your observations catch the bulk of stellar luminosity. For this reason, high values of \( BC \) 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, that therefore must univocally fix the “zero point” of the scale (Bessell, Castelli, & Plez 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 vs. temperature scale for cool red giants, where the intervening absorption of diatomic (\( \text{TIO in primis} \) 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 \( BC \) vs. \( \log T_{\text{eff}} \) 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 has actually 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 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) focussed on the possible impact of Helium abundance on \( BC \). As a major drawback of these efforts, however, one has to report the admitted limit of model atmospheres in 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, Arribas, & Martínez-Roger (1999), among others, trying to reconstruct stellar SED, and therefrom infer the bolometric flux, \( f_{\text{bol}} \), through optical broad-band photometry of stars in the Galactic field or in globular clusters. A recognized limit 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 multicolor photometry, alone, partially misses the bulk of stellar emission (more centered toward the NIR spectral window); in addition, by converting broad-band magnitudes into monochromatic

\(^1\) Recalling that emission peak roughly obeys the Wien law, i.e. \( T\lambda_{\text{peak}} \cong \text{const} \)

\(^2\) To a more detailed analysis, note that the ratio \( R \) 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 \( \lambda \).
flux densities, the stellar SED is reconstructed at 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. $[\text{Fe}/\text{H}] \approx -2.2$ dex) to super-solar ($[\text{Fe}/\text{H}] \approx +0.4$ 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 of our discussion, our procedure allowed us to sample about 70-90% 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 Sec. 2, our stellar database together with further available information in the literature. The analysis of the observing material will be assessed in more detail in Sec. 3, while in Sec. 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-color-temperature scale will be the focus of Sec. 5, especially addressing the possible dependence of BC on stellar metallicity. The comparison of our results with other relevant BC calibration in the literature will also be carried out in this section, while in Sec. 6 we will summarize the main conclusions of our work.

2 CLUSTER DATABASE SELECTION

As we mainly aim 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 [Fe/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 Pop 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 ~20 suitable targets have then been identified among the brightest and coolest red giants from the 2MASS infrared c-m diagram (Skrutskie et al. 2006). In assembling the dataset we also took care of picking up those objects out of more severely crowded regions of the clusters, and clearly recognizable in bright asterisms 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 the series of 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 (col. 1) and the alternative cross-identification, according to other reference photometric catalogs, 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 $B, V, R, I, c$ observed magnitudes according to the best reference catalogs for each cluster, as reported in the literature. When required, dereddened apparent magnitudes have been computed according to the color 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 June and October 2003 at the 3.5m Telecopia 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.

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) and a red setup (grism LRR, between $\lambda \lambda 4500 - 10300$ Å). In both cases the grisms provided a dispersion of 2.8 Å px$^{-1}$ on a 2048 × 2048 thinned and back-illuminated Loral CCD, with a 13.5μm pixel size. In order to collect the entire flux from target stars, we observed through a 5′′ wide slit; this condition actually made spectral resolution to be eventually constrained by the seeing figure (typically about 1-1.5′′ along the different nights), thus ranging between 10 and 15 Å (FWHM). This is equivalent to a value of $R = \lambda/\Delta\lambda$ between 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 1024×1024 Hawaii-1 HgCdTe detector. We took advantage of NICS unique design using the Amici grism coupled

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.
Table 1. Cluster properties and stellar database for cluster M 15

| ID              | E(B–V) = 0.10 | [Fe/H] = −2.26 |
|-----------------|---------------|----------------|
| (a)             | (b)           | (c)            |
| 21300902+1209182 | 0.65          | 11.93          |
| 21295705+1208531 | 0.95          | 12.02          |
| 21295532+1210327 | 3.67          | 12.13          |
| 21300900+1208571 | 5.58          | 12.20          |
| 21295473+1208592 | 3.30          | 12.28          |
| 21300461+1210327 | 3.69          | 12.35          |
| 21295560+1209056 | 7.00          | 12.45          |
| 21295082+1211301 | 21.30.04.32   | 12.56          |
| 21295739+1209056 | 21.30.10.49   | 12.64          |
| 21295569+1209425 | 621           | 12.73          |
| 21300974+1210375 | 65            | 12.82          |
| 21295431+1210561 | 368           | 12.91          |
| 21301049+1210061 | 621           | 12.99          |
| 21300739+1209175 | 21.30.07.40   | 12.10          |
| 21295881+1209285 | 59            | 12.19          |
| 21295164+1209175 | 21.30.50.54   | 12.28          |
| 21295739+1209056 | 21.30.19.81   | 12.37          |
| 21295569+1209425 | 621           | 12.46          |
| 21300974+1210375 | 65            | 12.55          |
| 21295431+1210561 | 368           | 12.64          |
| 21301049+1210061 | 621           | 12.73          |
| 21295739+1209056 | 21.30.07.40   | 12.10          |
| 21295881+1209285 | 59            | 12.19          |
| 21295164+1209175 | 21.30.50.54   | 12.28          |

(a) from 2MASS;  
(b) from Cohen, Briley, & Stetson [2005];  
(c) from Rosenberg et al. [2000]

Table 2. Cluster properties and stellar database for cluster M 2

| ID              | E(B–V) = 0.06 | [Fe/H] = −1.62 |
|-----------------|---------------|----------------|
| (a)             | (b)           | (c)            |
| 21333827-0054569 | 23.33.38.28   | −0.54.56.92    |
| 21333905-0052154 | 23.33.30.96   | −0.52.15.47    |
| 21332468-0042252 | 23.33.24.69   | −0.44.25.25    |
| 21331771-0047273 | 23.33.17.71   | −0.47.27.31    |
| 21331723-0048171 | 23.33.17.24   | −0.48.17.10    |
| 21331790-0048198 | 23.33.17.91   | −0.48.19.82    |
| 21331854-0051563 | 23.33.18.55   | −0.51.36.55    |
| 21331948-0051034 | 23.33.19.49   | −0.51.03.42    |
| 21331923-0049058 | 23.33.19.23   | −0.49.05.54    |
| 21332588-0046004 | 23.33.25.89   | −0.46.00.44    |
| 21336668-0051058 | 23.33.36.68   | −0.51.05.89    |
| 21335520-0046089 | 23.33.35.21   | −0.46.08.91    |
| 21334488-0047572 | 23.33.34.88   | −0.47.57.25    |
| 21334933-0049224 | 23.33.34.22   | −0.49.22.44    |
| 21334321-0051285 | 23.33.34.33   | −0.51.28.50    |
| 21332551-0052111 | 23.33.25.32   | −0.52.17.11    |
| 2133109-0054522  | 23.33.10.09   | −0.54.52.28    |
| 21333507-0051097 | 23.33.35.07   | −0.51.09.72    |

(a) all the data are from 2MASS;

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 a secondary calibrator (namely HD192281) 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 compilation. 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 all our observing runs, the night of Aug 07, 2003 displayed an outstanding (i.e. a factor of four higher than the average) dust extinction.

On the other hand, atmosphere water vapour can also play a role by affecting in unpredictable ways the infrared observations. Telluric H₂O bands about 1.10, 1.38 and 1.88 μm (Fuenzalida & Alonso [1998]; Manduca & Bell [1979]), just restraining to the Amici wavelength range, may in fact strongly contaminate 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 compilation. 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 all our observing runs, the night of Aug 07, 2003 displayed an outstanding (i.e. a factor of four higher than the average) dust extinction.
Table 3. Cluster properties and stellar database for cluster M 71

| ID            | (α, δ) (J2000.0) | α             | δ       | B       | (β, γ) (J2000.0) | V       | Ic       | J       | H       | K       |
|---------------|------------------|----------------|---------|---------|----------------|---------|----------|---------|---------|---------|
| 0044253+8510455 | 5865 19:45:26   | 15.24          | 13.63   | 13.67   | 13.59           | 12.31   | 12.35    | 11.98   | 11.08   | 10.98   |
| 0047402+8511322 | 5867 19:44:25   | 15.18          | 13.58   | 13.62   | 13.48           | 12.13   | 12.19    | 11.44   | 11.29   | 10.89   |
| 0047386+8511215 | 5868 19:44:22   | 15.23          | 13.61   | 13.65   | 13.48           | 12.13   | 12.19    | 11.44   | 11.29   | 10.89   |
| 0047386+8511215 | 5868 19:44:22   | 15.23          | 13.61   | 13.65   | 13.48           | 12.13   | 12.19    | 11.44   | 11.29   | 10.89   |
| 0047402+8511322 | 5867 19:44:25   | 15.18          | 13.58   | 13.62   | 13.48           | 12.13   | 12.19    | 11.44   | 11.29   | 10.89   |
| 0047386+8511215 | 5868 19:44:22   | 15.23          | 13.61   | 13.65   | 13.48           | 12.13   | 12.19    | 11.44   | 11.29   | 10.89   |

(a) from 2MASS;  
(b) from Geffert & Maintz (2000);  
(c) from Rosenberg et al. (2000).

Table 4. Cluster properties and stellar database for NGC 188

| ID            | (α, δ) (J2000.0) | α             | δ       | B       | (β, γ) (J2000.0) | V       | Ic       | J       | H       | K       |
|---------------|------------------|----------------|---------|---------|----------------|---------|----------|---------|---------|---------|
| 0044525+8510455 | 5863 19:44:22   | 15.18          | 13.58   | 13.62   | 13.48           | 12.13   | 12.19    | 11.44   | 11.29   | 10.89   |
| 0047402+8511322 | 5867 19:44:25   | 15.18          | 13.58   | 13.62   | 13.48           | 12.13   | 12.19    | 11.44   | 11.29   | 10.89   |
| 0047386+8511215 | 5868 19:44:22   | 15.23          | 13.61   | 13.65   | 13.48           | 12.13   | 12.19    | 11.44   | 11.29   | 10.89   |
| 0047386+8511215 | 5868 19:44:22   | 15.23          | 13.61   | 13.65   | 13.48           | 12.13   | 12.19    | 11.44   | 11.29   | 10.89   |
| 0047402+8511322 | 5867 19:44:25   | 15.18          | 13.58   | 13.62   | 13.48           | 12.13   | 12.19    | 11.44   | 11.29   | 10.89   |
| 0047386+8511215 | 5868 19:44:22   | 15.23          | 13.61   | 13.65   | 13.48           | 12.13   | 12.19    | 11.44   | 11.29   | 10.89   |

(a) from 2MASS;  
(b) from Platais et al. (2003);  
(c) from Stetson, McClure, & VandenBerg (2004);  
(d) B and V photometry from SIMBAD.

3.2 Photometry and spectral “fine tuning”

The relevant database of broad-band photometry available in the literature for all stars in our sample can be usefully accounted for 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 to 5, a wide collection of photometric catalogs can be considered, providing multicolor photometry along the range spanned by LRS and NICS spectra. Facing the observed values, one can similarly derive a corresponding set of multicolor synthetic magnitudes relying on the assembled SED of each star. Operationally, from our $f(\lambda)$ values we need to numerically assess the quantity...
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Table 5. Cluster properties and stellar database for cluster NGC 6791

| NGC 6791: | E(B–V) = 0.117 | [Fe/H] = +0.4 |
|----------|----------------|-------------|
| (a)      | (b)            | (c)         |
| ID       | α (J2000.0)    | δ           |
| 19210807+3747494 | 6697 3475 19:21:08.07 | 37:47:49:41 15.279 15.225 |
| 19204971+3743426 | 10807 3502 19:20:49.72 | 37:43:42:67 15.554 15.563 |
| 19205259+3744281 | 10140 2228 19:20:52.59 | 37:44:28:18 15.715 15.732 |
| 19205580+3742307 | 11799 3574 19:20:55.80 | 37:42:30:75 16.307 16.297 |
| 19206711+3737074 | 11308 2478 19:20:67.11 | 37:37:07:46 16.000 15.984 |
| 19210112+3742134 | 12101 3407 19:21:01.12 | 37:42:13:45 15.942 15.928 |
| 19211606+3746462 | 12750 3475 19:21:16.06 | 37:46:46:26 15.472 15.442 |
| 19212366+3740376 | 12850 3475 19:21:23.66 | 37:40:37:63 15.727 15.707 |
| 19213236+3741190 | 13637 3475 19:21:32.36 | 37:41:19.04 15.722 15.702 |
| 19213659+3739334 | 13082 3475 19:21:36.59 | 37:39:33.44 15.796 15.776 |
| 19214237+3753402 | 13082 3475 19:21:42.37 | 37:53:40.28 15.871 15.851 |
| 19214674+3751186 | 13082 3475 19:21:46.74 | 37:51:18.60 15.871 15.851 |
| 19215252+3752154 | 3254 3502 19:21:52.52 | 37:52:15.46 15.282 15.262 |
| 19211764+3752459 | 2970 3475 19:21:17.64 | 37:52:45.90 16.186 16.166 |
| 19202345+3754578 | 1829 3475 19:20:23.45 | 37:54:57.82 14.592 14.572 |
| 19205149+3739334 | 20140 3502 19:20:51.49 | 37:39:33.44 14.592 14.572 |
| 19203285+3753488 | 2394 3475 19:20:32.85 | 37:53:48.87 15.056 15.036 |
| 19209641+3744452 | 9800 3475 19:20:96.41 | 37:44:45.28 14.670 14.650 |
| 19208082+3744317 | 10034 3475 19:20:80.82 | 37:44:31.71 15.353 15.333 |
| 19205219+3744208 | 10225 3475 19:20:52.19 | 37:44:20.81 16.421 16.401 |

(a) from 2MASS; (b) from Kaluzny & Racinski (1993); (c) from Stetson, Bruntt, & Grundahl (2003).

Table 6. Logbook of TNG observations along 2003

| Obs. date (2003) | Instrument | Targets | Standards† |
|------------------|------------|---------|------------|
| Jul 29 | LRS | NGC6791 | HD192281 |
| Jul 30 | LRS | NGC6791 | HD192281, SAO48300, WOLF1346 |
| Jul 31 | LRS | NGC6791 | HD192281, SAO48300, WOLF1346 |
| Aug 6 | LRS | M71 | HD192281, SAO48300, WOLF1346 |
| Aug 7 | LRS | M15 | HD192281, SAO48300, WOLF1346 |
| Aug 11 | NICS | | HD192281, SAO48300 |
| Aug 12 | NICS | | Voting |
| Aug 18 | NICS | M71 | HD192281 |
| Aug 19 | NICS | | Voting |
| Aug 20 | NICS | M15, M71, NGC6791 | HD192281, SAO48300, WOLF1346, NGC6791 |
| Aug 21 | LRS | M2 | HD192281 |
| Aug 23 | LRS | M2, M15 | HD192281 |
| Aug 26 | LRS | NGC6791 | HD192281 |
| Aug 27 | LRS | NGC6791 | HD192281 |
| Aug 31 | LRS | M71 | HD192281 |
| Sep 1 | NICS | M71, NGC6791 | HD192281 |
| Sep 3 | NICS | M2, M15, NGC6791 | SAO48300 |
| Sep 4 | NICS | NGC6791 | HD192281 |
| Sep 5 | NICS | NGC6791 | HD192281 |
| Oct 14 | NICS | NGC6791 | HD192281 |
| Oct 15 | NICS | M2 | HD192281 |

† HD192281 and WOLF1346 from optical calibration by Massey et al. (1988), SAO48300 from JHK photometric calibration by Hunt et al. (1998); Vega from Tokunaga & Vacci (2005).

$$m_{\text{syn}}^j = -2.5 \log \left[ \frac{\int f(\lambda) S(\lambda)^j \, d\lambda}{\int S(\lambda)^j \, d\lambda} \right] - 2.5 \log f_{\text{0}}^j$$ (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 $f_{\text{0}}^j$. 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 vs. observed color, according to the different photometric catalogs quoted in Tables 1 to 5. As typically two sources for $V$ magnitudes are available for most clusters, observed colors have been computed for each available $V$ dataset and are displayed with a different marker (either dot or square) in the plots.

Just a glance to Fig. 2 makes evident that systematic offsets are present between observed photometry and synthetic magnitudes. This may partly be due to zero-point uncertainty in computing eq. (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 3σ 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 catalogs. 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 eq. (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%.

3.3 Stellar outliers

It could be interesting to analyze 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, 3σ 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 database indicates that at least 3 of them are known variable (typically semiregulars or irregulars), as expected for their nature of late-type red
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Figures 2 and 3. 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 vs. literature colors, according to the data of Table 1 to 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 datasets appear therefore twice in the plots and are singled out by dot and square markers, respectively.

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 to 5. Dashed vertical lines mark the ±3σ clipping edges, according to our iterative procedure, as devised in Sec. 3.2. Mag residuals are in the sense “obs” – “syn”. After outliers rejections, the global sample of 458 measurements has, on average, σ(∆mag) = ±0.095 (see Table 7).

Table 7. Magnitude residuals between observed and theoretical magnitudes

| Band | (Obs - Syn) | σ   | N_in | N_out |
|------|-------------|-----|------|-------|
| B    | -0.137      | 0.113 | 63   | 10    |
| V    | -0.091      | 0.094 | 72   | 1     |
| R_c  | +0.205      | 0.085 | 6    | -     |
| I_c  | +0.244      | 0.085 | 38   | 2     |
| J    | -0.093      | 0.069 | 88   | 9     |
| H    | -0.012      | 0.102 | 94   | 3     |
| K    | +0.197      | 0.102 | 97   | -     |
| total| 0.000^(b)   | 0.095 | 458  | 25    |

(a) Mag residuals are in the sense of observed – synthetic one (b) Weighting with the number of entries, N_in.

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.

4 No firm conclusions can be drawn, on the contrary, for the other seven cases, although it is evident even from a color check
Table 8. Standard synthetic photometry from SED of target stars in globular clusters M 71, M 15, and M 2

| ID         | V   | R_c  | I_c  | J   | H   | K   |
|------------|-----|------|------|-----|-----|-----|
| 21300004+2120112 | 15.11 | 14.30 | 13.81 | 13.27 | 12.58 | 12.08 |
| 21295075+2108531 | 14.30 | 13.35 | 12.79 | 12.18 | 11.41 | 10.82 |
| 21295532+1201327 | 15.34 | 14.43 | 13.85 | 13.24 | 12.50 | 11.94 |
| 21300004+2120571 | 14.04 | 12.90 | 12.21 | 11.47 | 10.51 | 9.82  |
| 21295473+2108592 | 14.89 | 13.90 | 13.19 | 12.55 | 11.62 | 10.92 |
| 21300341+1201037 | 15.01 | 14.35 | 13.24 | 12.62 | 11.86 | 11.16 |
| 21295560+1212422 | 14.59 | 13.46 | 12.86 | 12.23 | 11.41 | 10.79 |
| 21300514+1201401 | 15.20 | 14.31 | 13.79 | 13.23 | 12.45 | 11.89 |
| 21295836+2109020 | 14.80 | 13.83 | 13.27 | 12.65 | 11.81 | 11.22 |
| 21295816+2109179 | 14.02 | 12.89 | 12.19 | 11.48 | 10.49 | 9.82  |
| 21295795+2109056 | 14.89 | 13.83 | 13.22 | 12.58 | 11.65 | 11.05 |
| 21300097+1201375 | 14.91 | 13.85 | 13.24 | 12.63 | 11.85 | 11.19 |
| 21300431+1201256 | 14.76 | 13.91 | 12.92 | 12.25 | 11.40 | 10.86 |
| 21301049+1201061 | 14.45 | 13.36 | 12.73 | 12.09 | 11.25 | 10.60 |
| 21300773+1201330 | 15.22 | 14.05 | 13.67 | 12.66 | 11.84 | 11.24 |
| 21300569+1201201 | 14.02 | 11.41 | 11.56 | 12.97 | 12.21 | 11.61 |
| 21300553+1208553 | 14.82 | 14.84 | 14.66 | 13.61 | 12.50 | 11.86 |
| 21305675+2109438 | 13.80 | 14.25 | 11.72 | 11.01 | 10.10 | 9.47  |
| 21295802+2112139 | 14.61 | 13.56 | 12.91 | 12.27 | 11.80 | 11.02 |
| 21295881+1209285 | 14.62 | 13.40 | 12.70 | 12.03 | 11.17 | 10.57 |
| 21295716+2109175 | 13.96 | 13.03 | 12.45 | 11.84 | 10.98 | 10.36 |

Table 9. Standard synthetic photometry from SED of target stars in open clusters NGC 188 and NGC 6791

| ID         | V   | R_c  | I_c  | J   | H   | K   |
|------------|-----|------|------|-----|-----|-----|
| 00445223+8515055 | 13.65 | 12.34 | 11.66 | 11.01 | 10.04 | 9.41  |
| 00457823+8515322 | 13.68 | 12.13 | 11.38 | 10.73 | 9.78  | 9.20  |
| 00465964+8513157 | 13.87 | 12.40 | 11.71 | 11.10 | 10.25 | 9.71  |
| 00435976+8515084 | 15.49 | 13.90 | 13.10 | 12.40 | 11.44 | 10.87 |
| 00442946+8515093 | 15.84 | 14.28 | 13.44 | 12.73 | 11.81 | 11.27 |
| 00473224+8516024 | 15.79 | 14.24 | 13.40 | 12.73 | 11.87 | 11.40 |
| 00558226+8512209 | 12.28 | 10.82 | 10.06 | 9.34  | 8.31  | 7.59  |
| 00463920+8523336 | 12.89 | 11.56 | 10.87 | 10.21 | 9.19  | 8.53  |
| 00472975+8524140 | 14.05 | 12.91 | 12.33 | 11.74 | 10.70 | 10.11 |
| 00441424+8509312 | 12.81 | 11.28 | 10.45 | 9.86  | 8.60  | 7.85  |
| 00432964+8509375 | 14.17 | 13.14 | 12.61 | 12.08 | 11.25 | 10.76 |
| 00471847+8519456 | 14.89 | 13.03 | 12.19 | 11.47 | 10.54 | 9.99  |
| 00469184+8520086 | 14.58 | 12.50 | 11.60 | 10.88 | 9.98  | 9.43  |
| 00463904+8515158 | 15.67 | 14.20 | 13.45 | 12.78 | 11.91 | 11.42 |
| 00490560+8528077 | 13.89 | 12.65 | 12.02 | 11.41 | 10.48 | 9.90  |
| 00420324+8528982 | 11.29 | 9.75  | 9.81  | 8.14  | 7.05  | 6.43  |

(a) After correction for the systematic offsets, according to Table 7
(b) Dropped: B, J outlier;
(c) Dropped: B; H outlier;
(d) Dropped: B, J outlier;
(e) Dropped: B, J, H outlier;
(f) Dropped: B, J, H outlier;
(g) Dropped: B; H outlier;
(h) Dropped: B, J outlier;
(i) V13 + Var? [de Marchi et al. 2007].
(j) V70 ≡ SBG 2240: Ir var [Mochieska, Stanek, & Kaluzny 2003]

4 SPECTRAL ENERGY DISTRIBUTION AND BOLOMETRIC LUMINOSITY

The synthetic photometric catalogs obtained from the observed spectral database had a twofold aim: firstly, this procedure allowed to identify the observational sources of the bluer wavelength regions of both the LRS and NICM spectra, respectively. This coincidence might perhaps indicate some hidden problem with the flux calibration procedure during the observation of this cluster.

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5 Curiously enough, however, one may note that 6 out of the 7 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 NICM spectra, respectively. This coincidence might perhaps indicate some hidden problem with the flux calibration procedure during the observation of this cluster.
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Figure 4. Color distribution of photometric outliers, according to our 3σ clipping procedure (see Fig. 3). Target location for the whole star sample in the synthetic vs. observed color planes are displayed, with dark solid dots marking the “dropped” objects (see Table 10).

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

| Cluster ID | Outlier in | Notes |
|------------|------------|-------|
| B | V | R | I<sub>c</sub> | J | H | K |
| M15 | 180 | ... | ... | ... | ... | ... | ... | Z Sge - SRA P~ 175<sup>d</sup> |
| M71 | 4212 | x | ... | ... | ... | ... | ... | V2 48.1928 - Ir |
| 5755 | ... | x | ... | ... | ... | ... | ... | ... |
| N188 | 567 | ... | ... | x | ... | ... | ... | ... |
| 652 | x | ... | ... | x | ... | ... | ... | ... |
| 1109 | ... | x | ... | ... | ... | ... | ... | (K<sup>-6.15</sup>) |
| 630 | x | ... | ... | x | ... | ... | ... | ... |
| 174 | x | ... | ... | x | ... | ... | ... | ... |
| 1352 | x | ... | ... | x | ... | ... | ... | ... |
| N6791 | 3502 | ... | ... | x | ... | ... | ... | V13 - Var? |
| Tot | 7 | 1 | 0 | 3 | 6 | 2 | 0 |... |

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 M 15 stars, the strong impact of telluric water vapor bands at 1.38 and 1.88 μm. Their variability along the observing nights prevented, in some cases, any accurate cleaning procedure. See discussion in Sec. 3.1.

us to self-consistently match broad-band magnitudes with the inferred measure of $m_{bol}$, 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 $m_{bol}$.

Operationally, for the latter task, we proceeded as follows. Taking into account the individual set of $(Obs - Syn)$ magnitude residuals, for each star in our sample we computed a mean optical and infrared offset ($\Delta m_{LRS}$ and $\Delta m_{NICS}$, respectively) by separately averaging the $B, V, R, I_c, J, H, K$ mag residuals. The LRS spectra and the NICS observations have been then been matched by multiplying visual and IR fluxes by a factor $10^{-0.4(\Delta m_{LRS})}$ and $10^{-0.4(\Delta m_{NICS})}$, 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 color excess $E(B-V)$ is from the headers of Tables 1 to 5. In its final form, the SED is reshaped such as $f_\nu(\lambda) = f(\lambda) 10^{0.4 k(\lambda) E(B-V)}$. 


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. Note, from the figure, the striking presence of the CO bump about 1.6 μm (Frogel et al. 1978; Lançon & Mouhcine 2002), as well as the broad H$_2$O absorption bands to which the sharper (and variable) emission of telluric water vapor 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 Sec. 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. 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 (1973), Bessell (1979), Blackwell, Petford, & Shallis (1980), Riderway et al. (1980), Bessell, Castelli, & Plez (1998), Houdashelt, Bell, & Sweigart (2000), Vandenberg & Clerc (2003), Bertone et al. (2004) and Worthev & Led (2006). In their exhaustive analysis, Alonso, Arribas, & Martínez-Roger (1999) provided an accurate analytical set of fitting functions, that calibrate stellar effective temperature vs. Johnson/Cousins broad-band colors. The Alonso, Arribas, & Martínez-Roger (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 ($-3.0 \lesssim [Fe/H] \lesssim +0.2$). Within this range, the Authors claim an internal accuracy in the definition of $T_{\text{eff}}$ better than 5%. As a further important result of their work, some colors, like $(V - I)$, $(V - I')$, $(J - K)$ and $(I - K)$ are found to be fair tracers of temperature, almost independently from stellar metallicity. The Alonso, Arribas, & Martínez-Roger (1999) calibration, however, strictly applies only to stars warmer than $\sim 4000$ K, while our stellar sample definitely spans a wider color 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 color, like $(B - V)$ tends naturally to saturate when moving to $T_{\text{eff}} \lesssim 4000$ K (Johnson 1966, see also Fig. 2 in Alonso, Arribas, & Martínez-Roger, 1999). Considering the whole set of the Alonso et al. fitting functions, we eventually chose four reference colors to assess the value of effective temperature for our stars. Two colors, 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 colors we also added $(V - L_e)$ and $(V - K)$, as they provided a check of our flux calibration bridging the optical and infrared regions of the spectra.

Dereddened colors for each stars in our sample provided eventually 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 Table 11 and 12 (column 10). In case of just one $T_{\text{eff}}$ estimate (typically from $(J - K)$ color) we also added the $(V - K)$ output (reported in italics in the tables) trusting on a fairly smooth trend of the Alonso, Arribas, & Martínez-Roger (1999) calibration for this color, when extrapolated to cooler temperatures (see Fig. 8 and Fig. 10 therein).

Once combining the different temperature estimates from the four reference colors in our analysis, we report in Fig. 8 the resulting $T - (T)$ 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 2-4 useful temperature estimates are available from the colors of each star (see, again, Table 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%) internal uncertainty.

4.2 Toward $m_{\text{bol}}$

The fiducial effective temperature, as reported in col. 10 of Table 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; from 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 “overflown” 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 (Т) as in Table 11 and 12. The two spectral branches have separately rescaled to the (dereddened) flux values of the observed SED by setting the boundary wavelengths respectively at 4000 Å and 22500 Å; the integrated luminosity has then been computed within the three relevant regions of each stellar SED, identifying the ultraviolet contribution \( I_{UV} \) (between 0 \( \leq \lambda \leq 4000 \) Å) an optical/mid-infrared luminosity \( L_{obs} \) (4000 \( \leq \lambda \leq 22500 \) Å) and a far-infrared contribution \( L_{FIR} \) (longward of 2.25 \( \mu m \)). For comparison, the same exercise has been repeated for a straight black-body spectral distribution exploring the luminosity fraction emitted shortward of \( \lambda \leq 4000 \) Å and longward of \( \lambda \geq 22500 \) Å 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 $F_l = (L_{bol} - L_{obs})/L_{bol}$, turns to be about 15% for the bulk of red giants in our sample; this figure can however quickly raise with decreasing temperature, and about 1/3 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 $m_{bol}$ can be secured for our sample stars within a few 0.01 mag uncertainty.

Starting from the bolometric flux (which also includes the unsampled luminosity fraction, according to our procedure), the apparent magnitude for each star derives as $m_{bol} = -2.5 \log f_{bol} + Z.P.$, where $f_{bol}$ is the bolometric flux. If we assume for the Sun an absolute $M_{bol} = +4.72$, and $L_\odot = 3.89 \times 10^{33}$ erg s$^{-1}$, the bolometric zero point directly derives as Z.P. = −11.50 mag. On the same line, the BC scale is fixed once adopting an observed value for the apparent $V$ magnitude of the Sun. Following [Land 1993], if $m_V^{\odot} = -26.78$, then $M_V^{\odot} = +4.79$ and a $BC_V = -0.07$ mag derives. Our output, for the whole stellar sample, is reported in col. 11 of Table 11 and 12 together with the relevant (dereddened) BC to the $V$ and $K$ photon.

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

| ID         | (B-V)$_0$ | (V-K)$_0$ | (V-I)$_0$ | T$_{eff}$ (K) | T$_V$ (K) | T$_K$ (K) | T$_I$ (K) | (T)$_0$ (K) | Bol$_0$ | BC$_V$ | BC$_K$ |
|------------|-----------|-----------|-----------|---------------|-----------|-----------|-----------|------------|--------|--------|--------|
| 00445233+851405 | 1.22      | 1.20      | 2.66      | 0.55          | 4398      | 4354      | 4470      | 4854        | 4519   | 11.552 | -0.53  |
| 00475922+851132 | 1.46      | 1.27      | 2.65      | 0.49          | 4040      | 4243      | 4478      | 5078        | 4460   | 11.311 | -0.56  |
| 00456996+853135 | 1.38      | 1.16      | 2.30      | 0.54          | 4153      | 4422      | 4602      | 4889        | 4516   | 11.701 | -0.44  |
| 00554526+851220 | 1.34      | 1.35      | 3.05      | 0.73          | 4211      | 4129      | 4201      | 4309        | 4212   | 9.842  | -0.72  |
| 00639020+852333 | 1.24      | 1.22      | 2.83      | 0.65          | 4366      | 4321      | 4344      | 4530        | 4390   | 10.706 | -0.60  |
| 00672975+852414 | 1.05      | 1.04      | 2.70      | 0.68          | 4695      | 4650      | 4439      | 4444        | 4557   | 12.166 | -0.49  |
| 00441412+850931 | 1.44      | 1.47      | 3.27      | 0.78          | 4068      | 3981      | 4078      | 4184        | 4078   | 10.165 | -0.86  |
| 00432696+850917 | 0.94      | 0.93      | 2.32      | 0.62          | 4909      | 4893      | 4772      | 4621        | 4799   | 12.578 | -0.31  |
| 00490560+852607 | 1.15      | 1.11      | 2.45      | 0.47          | 4516      | 4513      | 4646      | 5159        | 4708   | 11.945 | -0.45  |
| 00420332+852049 | 1.45      | 1.48      | 3.32      | 0.81          | 4054      | 3970      | 4052      | 4114        | 4048   | 8.628  | -0.87  |

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 λ < 4000 Å, small square markers on the plot) and long (i.e. for λ > 2.25μm, small triangles) wavelength is sized up by extrapolating the observed SED with two black-body (BB) “wings” at fixed (T), as from col. 10 of Table 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.
Bolometric correction of cool stars

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

metric bands ($BC_V$ and $BC_K$, respectively in col. 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 colors 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 BC$_V$.

5.1 BC-color-temperature relations

Like for a color-color diagram, the BC vs. color relationship can be regarded as an intrinsic (i.e. distance-independent) feature characterizing the stellar SED. On the corresponding theoretical side, we want also 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 differently metal-poor ([Fe/H] $<-1$ dex, dots) and metal-rich ([Fe/H] $>-1$ dex, triangles) objects. For better convenience in our study, we also fitted the overall distribution analytically; a useful set of fitting functions for the BC vs. $T_{\text{eff}}$ relations along the $3300 \lesssim T_{\text{eff}} \lesssim 5000$ K temperature range results:

\begin{align}
BC_V &= -\exp(27500/T_{\text{eff}})/1000 \\
(\sigma_{BC}, \rho) &= (0.11, 0.989) \\
BC_K &= -6.75 \log(T_{\text{eff}}/9500) \\
(\sigma_{BC}, \rho) &= (0.05, 0.978)
\end{align}

(4)

As for the color relations, the non-monotonic trend of $BC_V$ vs. $(B-V)$ (see left upper panel in Fig. 8) prevents us to use the color as 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 of the previous equation set, eventually results:

\begin{align}
(B - V) &= 1.906 \left[BC_V \exp(BC_V)\right]^{0.3} \\
(\sigma_{BV}, \rho) &= (0.11, 0.863) \\
V - K &= 1/(1 - 0.283 BC_K) \\
(\sigma_{VK}, \rho) &= (0.13, 0.991)
\end{align}

(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 \((B-V)\) vs. \(B_V\) behaviour at very low temperature. From one hand, in fact, the interposing effect of the TiO absorption at visual wavelength \(\text{Kučinskas et al. 2005}\) makes the \((B-V)\) color of stars cooler than \(\sim 3700\) K to strongly saturate reaching a maximum of about \((B-V)_\text{max} \sim 1.5\) and turning back to bluer values for later M-type stars. On the other hand, the apparent trend of our sample in this range is evidently biased by the NGC 6791 stellar population with just a few super metal rich giants constraining the \(B_V\) 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 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 colors 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 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 \(\text{Kučinskas et al. 2005}\) 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 (cols. 12 and 13 in the tables) and the “mean” locus of eq. (4), once entering the equations with the fiducial (T) of col. 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 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, basic physics of stellar atmospheres leads to conclude that the \(V\)-band (and even more the \(K\)-band) luminosity are
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 straight "translate" this metallicity effect in terms of apparent ($B - V$) color change. This is shown in Fig. 11 where for each star in our sample we computed the residual ($B - V$) and ($V - K$) color as a difference between observed and expected values by entering eq. (5) with the fitted value of BC as from eq. (4). Metallicity is traced in the plot by the marker size (the bigger the marker the higher the [Fe/H] value); again, we discriminate between metal-poor (diamonds) and metal-rich (dots) stars, taking the value $[Fe/H] = -1.0$ dex as a reference threshold.

A trend of $\Delta(B - V)$ vs. cluster metallicity is now clearly evident, with the metal-poor and metal-rich star samples nearly segregated in the plot, the latter stars displaying a "redder" ($B - V$) color (and correspondingly a positive color 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 $V - K$ color as a virtually metal-independent feature.

Considering in more detail the $\Delta(B - V)$ distribution vs. cluster metallicity, a fit to the data provides:

$$-\Delta BC_B \equiv \Delta(B - V) = 0.10 \ [Fe/H] + 0.13 \pm 1.0 \pm 2$$

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

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 attempting to extend their analysis to cool ($T_{\text{eff}} \lesssim 3500$ 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) and Bessell, Castelli, & Plez (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 colors 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 $BC_V = -0.07 \text{ mag}$.

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 vs. observables (i.e. ($B - V$) and ($V - K$) colors, respectively) and theoretical ($T_{\text{eff}}$) reference quantities. In all respects, this figure is fully equivalent with, and can be compared to, Fig. 8 where we 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” vs. temperature consequent to the shifted emission toward 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 colors 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 $BC_V$ vs. ($B - V$) behaviour is concerned, the reference calibrations display the largest spread, with M98 predicting increasingly redder stars with decreasing temperature. At the opposite, NM predicts a sharp color “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, fairly well tracking the observations. This trend is very closely replid also 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.

By converting colors to the theoretical plane of effective temperature (right upper 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 eq. (4).

The situation is much eased in the infrared domain, where a
monotonic relationship between \((V-K)\) color and BC\(_K\) characterizes red giants 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\(_K\) ≃ 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 eqs. (4), (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 colors of M stars. As described by the authors, this 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

The 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 (3 globular + 2 open) Galactic clusters along the full metallic-
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Itty range from $[\text{Fe}/\text{H}] = -2.2$ up to +0.4 (see Sec. 3). Spectra cover the wavelength range from 3500 Å to 2.5μm, collecting optical and IR observations. A delicate task for the final settlement of our stellar database 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 $BVRI_{\text{c}}, JHK$ photometry available in the literature (Sec. 2 and 3). Allover, we are confident that stellar SED along the entire sampled wavelength range has been set up within a ±10% internal accuracy (see Table 7 and Fig. 1).

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 $T_{\text{eff}}$-color fitting functions, we took the four colors $(B-V)$, $(J-K)$, $(V-I_{\text{c}})$, and $(V-K)$ as a reference for our calibration, leading to constrain $T_{\text{eff}}$ for each stars in our sample within an estimated error better than ±100 K (see Sec. 4.1), along the whole spanned temperature range $(3300 \leq T_{\text{eff}} \leq 5000 \text{ K})$.

The fiducial temperature allowed us to shape the unsampled portion of the SED at UV and far-IR wavelength by assuming a black-body emission independently rescaled such as to connect the short and long wavelength edge of the observed spectra. As shown in Sec. 4.2 (see also Fig. 7), under the black-body 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 database, we have been able to draw a convenient set of fitting functions for the BC vs. $T_{\text{eff}}$, valid over the interval $3300 \leq T_{\text{eff}} \leq 5000 \text{ K}$ (see Sec. 5.1, eq. 3). Similar relationships for BC vs. stellar colors cannot be straightforwardly derived (eq. 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 (Kucinskas 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 ([Fe/H] = +0.4) hosts stars with $T_{\text{eff}} < 3700$ K.

Thanks to the wide [Fe/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 dominant lines among stars with $T_{\text{eff}} \gtrsim 4000$ K, our data confirm that no evident trend of BC with [Fe/H] is in place (see Fig. 7). In other words, two red giant stars of the same effective temperature but different [Fe/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 $BC_{K}$ vs. colors 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 limit for theory to independently assess the modelling of cool stars.

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