Astron. Astrophys. 289, 775–783 (1994)

ASTRONOMY AND ASTROPHYSICS

Synthetic and observed photometric indices for globular clusters in the Galaxy and M 31

S. Covino[1,2], L.E. Pasinetti Fracassini[1], M.L. Malagnini[3] and A. Buzzoni[2]

[1] Dipartimento di Fisica dell'Università, Via Celoria 16, I-20133 Milano, Italy
[2] Osservatorio Astronomico di Brera, Via Brera 28, I-20121 Milano, Italy
[3] Dipartimento di Astronomia dell'Università, Via Tiepolo 11, I-34131 Trieste, Italy

Received 13 September 1993 / Accepted 18 March 1994

Abstract. Buzzoni's (1989) grid of synthetic spectral energy distributions, representative of old stellar populations, was used to derive colours in different photometric systems, and to compare the theoretical predictions with the observational data referring to about 120 globular clusters in the Galaxy and to 159 objects of the globular cluster system of M 31.

Synthetic and observed indices display an overall agreement in the composite planes of two-colour diagrams, thus in agreement with the standard evolutionary scenario leading, for globular clusters, to old stellar populations consistent with an age of 15 Gyr and a Salpeter initial mass function (IMF). The two main parameters modulating the cluster colour distributions are, as known, metallicity and horizontal branch morphology, while IMF slope and mass loss rate from stars in the red-giant branch and asymptotic-giant branch evolutionary stages produce only minor, although not negligible, effects on the integrated colours.

The M 31 and Galactic cluster populations are found to be substantially similar, at least as far as the spectral energy distribution characteristics in the $U \rightarrow V$ spectral range are concerned.

In general, the model predictions are fully consistent with the cluster metallicity values given in the current metallicity scale for Galactic globular clusters (Zinn & West 1984) with some exceptions for the IR photometry, where the models predict $V-K$ values systematically bluer (by 0.1–0.2 mag) than the observed ones for metal-poor clusters. The question is discussed in some detail with reference to different data sources.

Key words: globular clusters: general – galaxies: M 31 – stars: population II – Galaxy: general

1. Introduction

Evolutionary synthesis of stellar populations provides a powerful tool for understanding the rôle of individual stellar components in the integrated radiation of stellar systems, such as clusters and galaxies, once models have been proved to be consistent with observations. In particular, evolutionary synthesis is able to explore also the influence of primary parameters like age, chemical composition, initial mass function and stellar mass loss, on the integrated spectral energy distribution (SED). A grid of over 450 theoretical models for old simple stellar populations (SSPs) was published by Buzzoni (1989; hereafter B89). These models take into account in a quantitative way the contribution from all the relevant stellar evolutionary phases according to the theory of stellar evolution. Thus, late stages in the life of low-mass stars, such as the horizontal branch (HB), and the asymptotic and post-asymptotic giant branches, were accounted for. Furthermore, a simple treatment for the HB evolution was developed, investigating the influence of different morphologies.

As a natural and important step for testing the consistency of those models, which are extensively used in the extragalactic domain (e.g. Buzzoni et al. 1992; Buzzoni 1993; Buzzoni et al. 1993; Bohlin et al. 1993; Hill et al. 1993), we decided to perform a systematic comparison of Buzzoni's theoretical framework with the current observational databases for Galactic and M 31 globular clusters. Multicolour photometry for over 120 globulars in the Galaxy and for 159 clusters in M 31 has been therefore collected from the literature, and will be analyzed here. A preliminary test on the models was made also by Di Toma (1989) using only a sample of Galactic clusters. The superior advantage of using Galactic globulars is that they offer a (still) unique chance to check in detail the overall morphology of their stellar populations in the c-m diagram.

The present work is intended to complement a more comprehensive approach to the study of globular clusters relying on multivariate data analysis (Covino & Pasinetti Fracassini 1993), and aims at investigating the influence of different physical parameters on the integrated photometric properties of stellar clusters, searching also for possible anomalous trends in some objects and/or groups.

We briefly describe in Sects. 2 and 3 the adopted theoretical framework and the observational database, respectively; in Sect. 4 a full comparison is performed discussing the match of models with observations in different colour planes and the

Send offprint requests to: L.E. Pasinetti Fracassini

metallicity scale for globular clusters. Our relevant conclusions will be summarized in Sect. 5.

2. Models and synthetic photometric indices

Full details in the construction of the models are discussed in detail in B89, and we will just summarize here some of the relevant features.

The integrated SEDs are based on the following sources: *i)* for main sequence stars, on the set of isochrones published by VandenBerg and collaborators (VandenBerg 1983, 1985; VandenBerg et al. 1983; VandenBerg & Bell 1985; VandenBerg & Laskarides 1987); *ii)* for the red giant branch (RGB), on the tracks by Sweigart & Gross (1978); *iii)* for the HB, on the tracks of Sweigart & Gross (1976), Seidel et al. (1987), Sweigart (1987); *iv)* for the asymptotic giant branch (AGB), on the works by Gingold (1974, 1976), Paczynski (1970, 1971, 1975), and Iben (1982), and *v)* for Post-AGB, on Paczynski (1970, 1971).

The SED of individual stars in the SSP is supplied by the theoretical fluxes computed from model atmospheres by Kurucz (1979, hereafter K79) and by Bell & Gustafsson (1978).

We selected from the whole B89 grid a subsample suitable for matching globular cluster characteristics, namely those computed for age $\tau = 10, 12.5, 15$ and 18 Gyrs, and metallicity $\log Z = -4.0, -3.0, -2.0$ (i.e. $[Fe/H] = -2.27, -1.27, -0.25$) with $Y = 0.23$. Two slopes for the initial mass function (IMF, taken in the canonical form $\phi(M) \propto M^{-s}$), have been assumed ($s = 1.35, 2.35$), and a Reimers mass-loss parameter η in the range 0.3–0.5.

HB evolution was accounted for by adopting the three reference morphologies given in B89 and attributed to 15 Gyr SSPs, namely: *i)* a blue HB (B-HB) like in NGC 6752, *ii)* an intermediate type HB (I-HB) like in M3, and *iii)* a red clump (R-HB) like in 47 Tuc. A representative sample of the whole grid of models is given in Fig. 1 by displaying the SED for I-HB SSPs with increasing age.

Starting from the relevant subsample of 44 models we derived synthetic colours in the Johnson & Cousins $UBVRIJK$, Thuan & Gunn $uvgr$, and Washington Observatory CMT_1T_2 systems. These photometric systems were selected because of the availability of extensive observational data from the literature, and because their band widths are compatible with the SED wavelength sampling.

In Fig. 2 the positions of the effective wavelengths for each filter are indicated; all the filter bands extend only longward of 3000 Å. On the same figure, the fluxes predicted from K79 grid for the atmosphere model with the parameters $T_{eff} = 5500\ K$, $\log g = 3.0$ dex, and solar chemical composition are plotted together with those predicted by using the more recent grid by Kurucz (1992; K92) ($T_{eff} = 5500$ K is the lowest value available in K79, and used in B89; for lower temperatures, Bell & Gustafsson 1978 models were used instead). The comparison between the two spectral energy distributions (both having colours in the same range of those of globular clusters) shows that only minor effects, especially in the ultraviolet range, can be expected when using K92 instead of K79 grid. Moreover, the differences, if any, will be further reduced for metallicities lower than solar, as in the case of globular cluster old populations, and for temperatures higher than 5500 K.

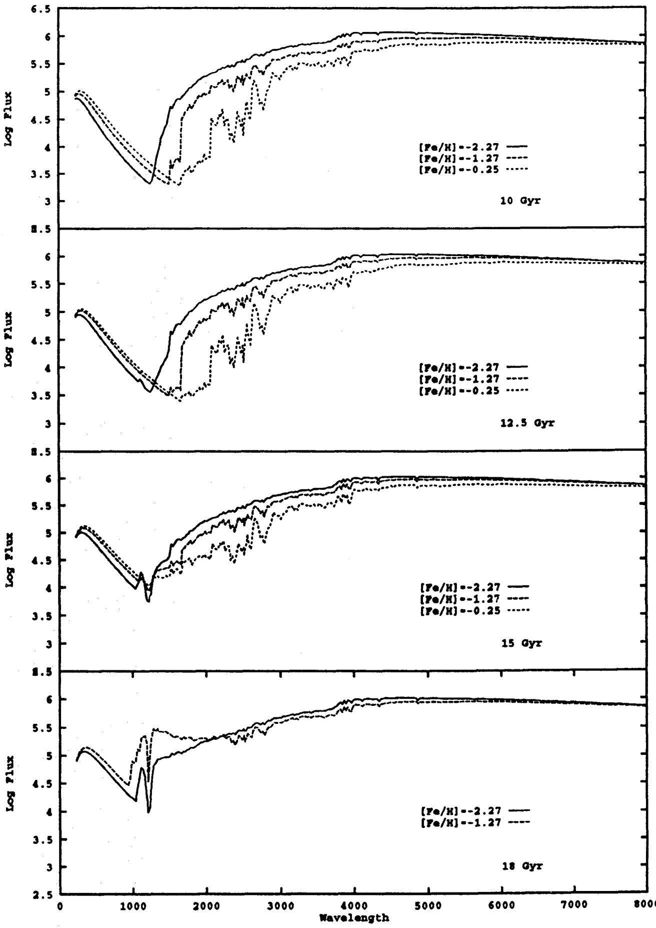

Fig. 1. Rôle of metallicity on the SEDs computed for I-HB morphology and for $\tau = 10, 12.5, 15, 18$ Gyr, $s = 2.35$ and $\eta = 0.5$

The synthetic colours in the Johnson system are from B89 based on Buser's (1978) prescriptions for matching the standard system, and on Hayes' & Latham's (1975) calibration of Vega to fix the magnitude zero points. The more recent calibration of Vega (Hayes 1985) has been also taken into account in order to test the internal self-consistency of the magnitude zero points confirming an excellent agreement throughout the different colours within a ± 0.02 mag uncertainty.

According to Buzzoni (1993), the U magnitudes for synthetic SSPs require however a further revision due to a more accurate account of the metal blanketing for stars having temperatures below 5500 K. In this range, B89 used Bell & Gustaffson (1978) model atmospheres that had to be extrapolated shortward of 3000 Å. To a more accurate analysis, this approximation resulted in a moderate enhancement of the UV flux in the stellar SED by slightly underestimating the blanketing. This result has an effect only for the U band while it is negligible at longer wavelengths. As a consequence, as shown in Buzzoni (1993), integrated $U - B$ colours in the range pertinent to globular clus-

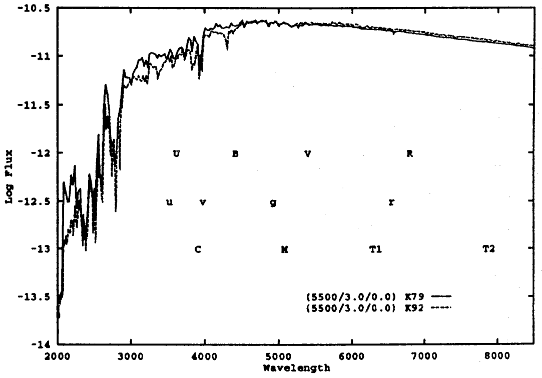

Fig. 2. Comparison between the fluxes predicted from K79 grid and those by K92. The positions of effective wavelengths for each filter are indicated

ters become now about 0.04 mag redder than in B89 due to this correction. This correction has been included throughout in our analysis.

The internal uncertainty in reproducing colours in the standard system is typically ±0.02 mag, a value that raises to ±0.05 mag for UV and IR extreme colours like $U - V$ and $V - K$ (B89).

Synthetic colours in the other systems were obtained with the same procedure, as fully described in Di Toma (1989). For the $uvgr$ system, the subdwarf BD+17°4708 (Thuan & Gunn 1976; Oke & Gunn 1983; Kent 1985) was adopted as primary photometric standard. Typical uncertainty values for all Thuan & Gunn indices are on the order of ±0.02 mag.

The calibration of synthetic CMT_1T_2 indices was based on the observations by Canterna (1976) for nine stars (spectral types from B to K) whose spectral energy distributions were available in the Vilnius spectral atlas (Straizys & Sviderskiene 1972). Uncertainties are in this case of the order of ±0.02 mag for $M - T_1$, and of ±0.05 mag for $C - M$ and $T_1 - T_2$.

3. Observational data and cluster parameters

A systematic scan of the current literature allowed us to collect data for more than 120 Galactic globular clusters (GGCs) spanning a wide range in c-m diagram morphology. Whenever available, for each cluster we collected the relevant colour indices in the different photometric systems, the E_{B-V} colour excess, the HB morphological parameters, and the metallicity [Fe/H]. In Table 1, we present a statistics of the available data, together with their main sources.

Although only for about 50% of the GGC sample we got a complete set of data, the statistics is enough to allow us to perform meaningful comparisons of theoretical predictions with observations.

At present, information on M 31 clusters are not as complete as for GGCs. An extensive UBV compilation of 159 objects is due to Elson & Walterbos (1988). Of these, 141 (their "sample A") are thought to be *bona fide* globular clusters. Less comprehensive, but we believe more homogenous and internally more

Table 1. Summary of data for GGCs used in this work

Parameters	No.	Sources
UBV	114	1,2
$V - R$	82	1,2
$V - I$	95	1,2
$V - K$	37	3,4
E_{B-V}	120	2,5
$uvgr$	79	6
CMT_1T_2	51	7
$[Fe/H]$	121	8
HB morphology	75	9,10,11,12

1. Reed (1985).
2. Reed et al. (1988).
3. Burstein et al. (1984).
4. Brodie & Huchra (1990).
5. Harris & Racine (1979).
6. Zinn (1980 a).
7. Harris & Canterna (1977).
8. Zinn & West (1984).
9. Hesser & Shawl (1985).
10. Straizys (1982).
11. Kukarkin (1974).
12. Alcaino (1979).

accurate observations, are those of Burstein et al. (1984; 19 clusters in UBVJK) and Reed et al. (1992; 76 clusters in $UBVR$). Also, the systematic infrared observations of the Bologna group (Bònoli et al. 1987) have been included in our analysis.

A direct knowledge of the Galactic cluster morphology, in particular of the HB and AGB morphology, allowed us to refine the comparison with the models by adopting the appropriate distinctive parameters for mass loss and HB extension. Though with some relevant exceptions dealing with the "second-parameter" problem (cf. Chiosi et al. 1992, and references therein), there is a well established relationship between HB morphology and metallicity, in the sense that the lower is metallicity the bluer is HB morphology (Zinn 1980b). A link to the models can be made by using the Hesser & Shawl (1985) parameter $B/(B + R)$ to quantify the HB "blueness". For instance, the templates NGC 6752 (B-HB), M3 (I-HB), and 47 Tuc (R-HB) have $B/(B + R)$ = 1.0, 0.5, and 0.0, respectively.

The estimated uncertainty in the Galactic cluster photometry as derived from the original sources is about ±0.02 mag for all colours accounted here except for $V - K$ for which ±0.20 mag is a fair value. For M 31 clusters, we find a larger uncertainty of nominally 0.05 mag from a combined comparison of objects in common with the different sources. Moreover, in this case also partial failures in the membership criteria to discriminate between genuine M 31 globulars and spurious objects could introduce a larger scatter in the data. We will further discuss in sect. 4.2 the problem of the relative accuracy in the M 31 cluster photometry.

4. Results and discussion

As a first step in our analysis, we will consider the influence of the physical input parameters on the derived SEDs; then the

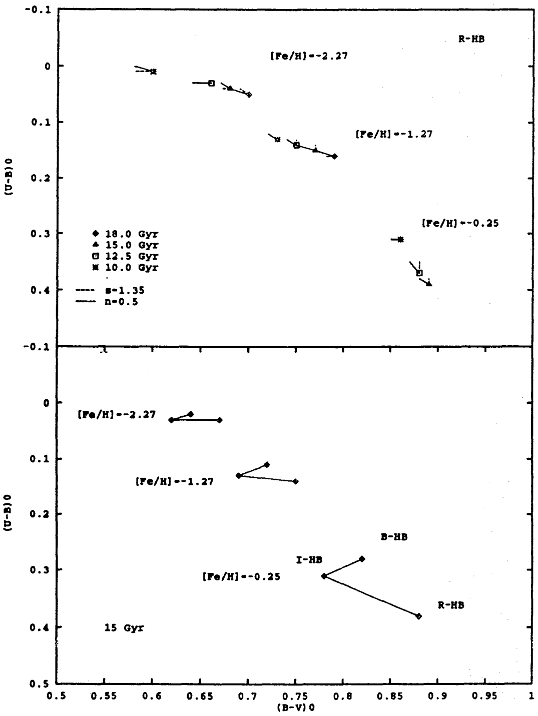

Fig. 3. The rôle of the physical input parameters on synthetic colour indices for R-HB morphology on the $U-B$, $B-V$ plane (top). The symbols correspond to the values of IMF and mass loss parameters s = 2.35 and η = 0.30. The dotted and solid lines give the shift obtained adopting the values s = 1.35, η = 0.5 respectively. The lower panel shows, for an age of 15 Gyr, s = 2.35, η = 0.5, the shifts on colour indices caused by different HB morphology

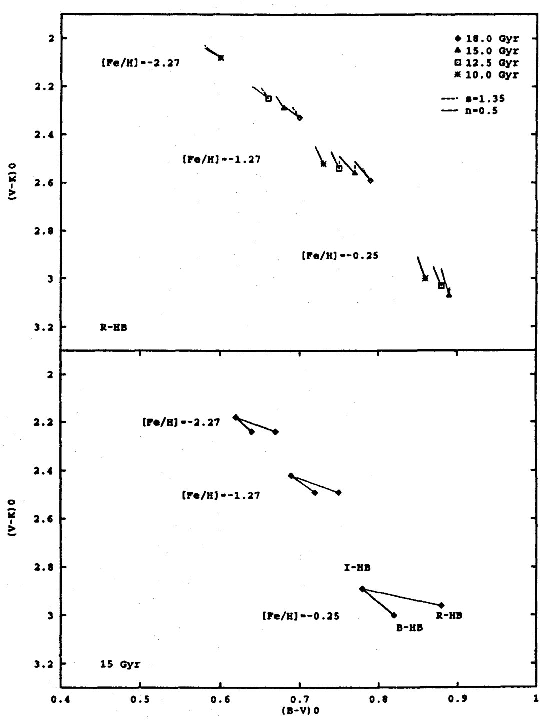

Fig. 4. As in Fig. 3, but on the $V-K$, $B-V$ plane

trend of the synthetic colours in two-colours diagrams will be accounted for, and compared with all available photometric data. Finally, the behaviour as a function of metallicity will be discussed in more detail.

4.1. Physical input parameters

An overall view of the colour trend depending on the different distinctive parameters of the SSPs is shown in the four panels of Figs. 3 and 4. Top panels summarize the colour dependence in the plane $(U-B)/(B-V)$ and $(B-V)/(V-K)$ for a selective change in age, IMF, and mass-loss efficiency for SSPs with R-HB. As well recognized, metallicity is the leading parameter modulating the colour distribution throughout. A choice of a R-HB usually traces a red edge to the colour distribution for any fixed HB morphology. A blue envelope can also be located but quite curiously it does not necessarily correspond to a B-HB. In fact, it can be seen from lower panels of Figs. 3 and 4 that while $U-B$ keeps to decrease with increasing HB "blueness", both $B-V$ and $V-K$ reach a minimum and then turn back generating a hooked feature in the figure. This is due to the fact that a hot HB has a lesser impact on the visual and infrared colours, that on the contrary are mainly modulated by the underlying red bulk of the SSP. According to the Wien law, an HB star distribution peaked about 7000 K ($log\ T$ = 3.85, i.e. like in an I-HB morphology) should provide the bluest $B-V$ on the integrated SSPs while about 9000 K (roughly as in a B-HB) are necessary to reach the lowest $U-B$.

In any case, we have to expect that the influence of a different HB morphology does not pervasively affect integrated colours of globular clusters. For example, one sees from the figure that a change from R-HB to I-HB at $[Fe/H] \leq -1$ only causes a 0.05 mag variation in $B-V$, and even less in $U-B$.

In the following analysis, we will adopt model sequences computed for τ = 15 Gyr according to the current estimates for the age of globular clusters (Hesser 1993), and a Salpeter IMF. An I-HB morphology will be assumed at low metallicity ($[Fe/H] \leq -1$) smoothly matching a R-HB for metal-rich clusters. For reference, the B-HB sequence will also be tracked separately at low metallicity.

A mass-loss parameter η = 0.5 is adopted, more suitable for low-metallicity systems (Buzzoni 1993) as demanded by the observed equality in the luminosity of the AGB and RGB tip, a feature strongly modulated by mass loss (Iben & Renzini 1983; Renzini & Fusi Pecci 1988).

As it can be seen in Figs. 3 and 4, the influence of mass loss and IMF, when considered separately, introduces only a second-order effect on blue colour like $U-B$ or $B-V$ while it has a more striking impact on $V-K$. The general trend is in the sense of obtaining slightly redder colours by decreasing mass loss (due to a more extended AGB) or by adopting a steeper IMF (due to an enhanced contribution of red dwarfs supplying about 1/3 of the total K light in a Salpeter SSP, cf. B89). Quantitatively similar trends can be found also for other combinations

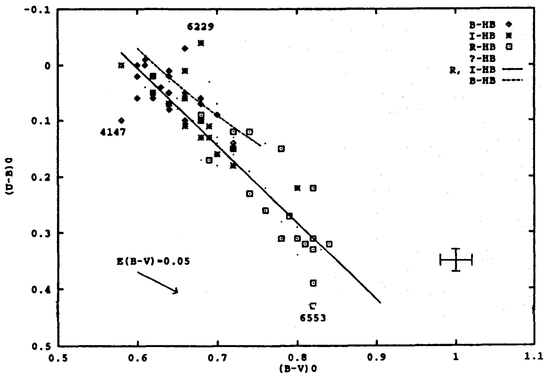

Fig. 5. Comparison between synthetic and observed indices for an age of 15 Gyr for 93 GGCs (Reed et al. 1988), on the plane $U-B$, $B-V$. The dotted line links the values of the synthetic indices computed for B-HB at lower metallicities. The solid line links computed indices for I-HB and R-HB morphology

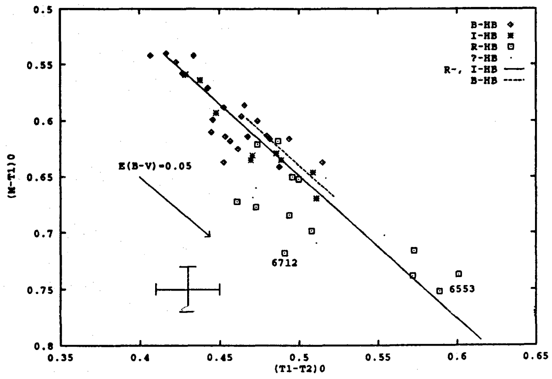

Fig. 7. Comparison between synthetic and observed indices for an age of 15 Gyr for 51 GGCs (Harris & Canterna 1977) on the plane $M-T_1$, T_1-T_2 of Washington Observatory system. Symbols as in Fig. 5

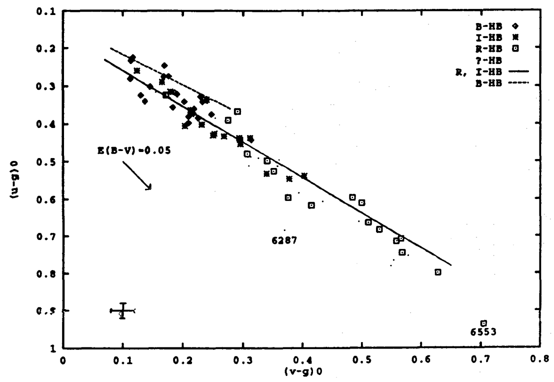

Fig. 6. Comparison between synthetic and observed indices for an age of 15 Gyr for 79 GGCs (Zinn 1980a) on the plane $u-g$, $v-g$ of Thuan & Gunn system. Symbols as in Fig. 5

of colours involving for example Thuan & Gunn or Washington indices.

4.2. Comparison with observations

Model predictions have been compared with the observational data for Galactic and M 31 globular clusters in two-colour diagrams referring to the various photometric systems available. In order to make the observed colours comparable to the synthetic ones, we corrected for reddening according to the adopted $E(B-V)$ taken from the literature for both Galactic and M 31 systems. We present herewith the most interesting results; other colours should be used with more caution.

Figure 5 shows a comparison in the $(U-B)_o/(B-V)_o$ plane for 93 GGCs. Regarding the observational points, we remark that the HB morphology is not available for all the clusters in an homogeneous way, and when possible, we inferred it from the published $B/(B+R)$ parameter in order to roughly match Alcaino's (1979) classification. Therefore, a R-HB is assumed for $B/(B+R) \leq 0.3$, an I-HB is attributed in the range $0.3 \leq B/(B+R) \leq 0.7$ and a B-HB morphology for $B/(B+R) \geq 0.7$.

According to our discussion in the previous section, it is relevant to note in the figure the effect of colour saturation that causes the B-HB theoretical locus to be even redder than the I-HB locus in $B-V$ (but still bluer in $U-B$). To a large extent such a complex behaviour explains the difficulty in a proper discrimination of the cluster HB morphology starting from the multicolour photometry alone.

As already pointed out also by Reed et al. (1988), three clusters, namely NGC 6553, 4147 and 6229, lie in Fig. 5 in a position rather discrepant from the general trend. Of these, NGC 6553 is on the Galaxy disk (galactic distance R = 2.9 kpc, $[Fe/H]$ = –0.29) and might have a poor determination of the reddening.

Regarding Thuan & Gunn photometry, the best combination maximizing point correlation seems a $(u-g)_o$ vs. $(v-g)_o$ plot as shown in Fig. 6 for 79 GGCs. It is worth mentioning that any colour involving r magnitudes gives on the contrary an exceedingly high scatter of the points (difficult to say whether intrinsic or instrumental) among high-metallicity clusters.

The most discrepant point in the figure is for NGC 6287 ([Fe/H]=–2.05). This cluster of low-concentration class, was already pointed out by Reed et al. (1988) for its anomalous position in two colours diagrams of their $UBVRI$ photometry.

Similar results hold also for the Washington system, as summarized in Fig. 7 in the $(M-T_1)_o$ vs. $(T_1-T_2)_o$ plane for 51 GGCs. Again, the agreement between computed and observed colours is rather satisfactory. The clusters in a position discrepant from the general trend about $[Fe/H] \sim -1$ are on or near the galactic disk and belong to the central region of the Galaxy.

In particular, NGC 6712 was already pointed out by Reed et al. (1988) for problems in the spectral classification. However, we note that this cluster completely lies into the standard locus of the Galactic globulars in the Johnson and Thuan & Gunn photometry.

Regarding the M 31 sample, UBVJK observations of Burstein et al. (1984) for a selected list of objects and the largest compilation of Elson & Walterbos (1988) and Reed et al. (1992) are taken into account in Figs. 8, 9, and 10, respectively. In addi-

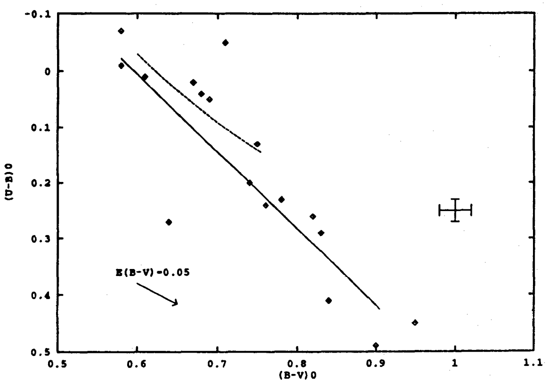

Fig. 8. Comparison between synthetic and observed indices from Burstein et al. (1984) for an age of 15 Gyr for 17 M 31 clusters on the plane $U-B$, $B-V$. Dotted and solid lines as in Fig. 5

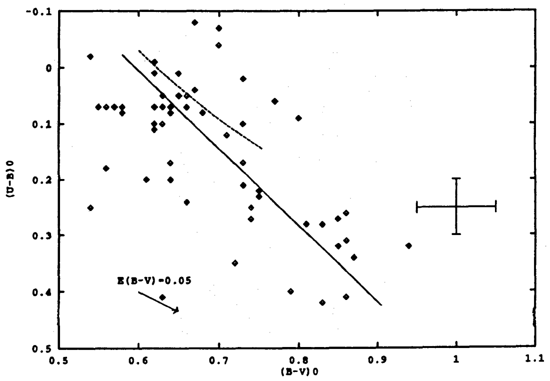

Fig. 10. Comparison between synthetic and observed indices for 65 M 31 GCs (Reed et al. 1992) for an age of 15 Gyr on the plane $U-B$, $B-V$. Dotted and solid lines as in Fig. 5

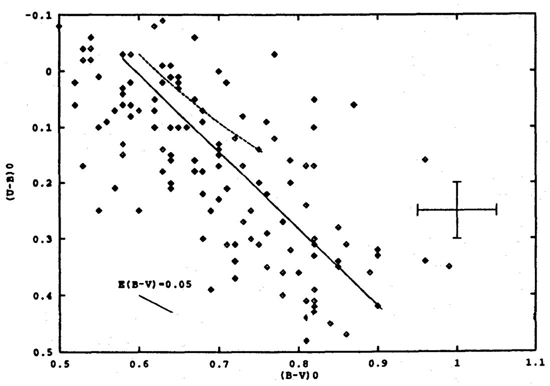

Fig. 9. Comparison between synthetic and observed indices for 141 M 31 GCs (Elson & Walterbos 1988) for an age of 15 Gyr on the plane $U-B$, $B-V$. Dotted and solid lines as in Fig. 5

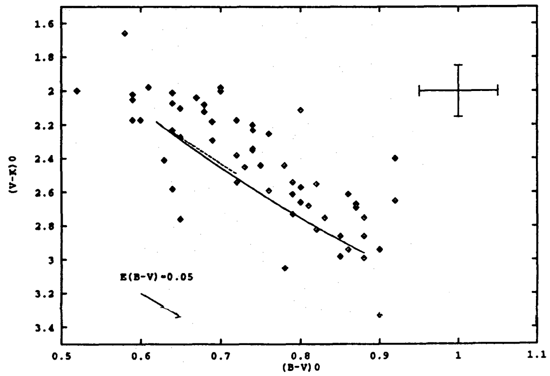

Fig. 11. Comparison between synthetic and observed indices for 68 M 31 GCs (Bònoli et al. 1987) for an age of 15 Gyr on the plane $V-K$, $B-V$. Dotted and solid lines as in Fig. 5

tion, the largest infrared sample supplied by the Bologna group (Bònoli et al. 1987) is given in Fig. 11.

As well known, to some extent the M 31 and Galaxy system of clusters seem to have much in common from the evolutionary point of view (Frogel et al. 1980; Burstein et al. 1984; Elson & Walterbos 1988; Covino & Pasinetti Fracassini 1993), and also recent space observations in the far UV (Bohlin et al. 1993) confirm that spectral properties for almost the totality of M 31 clusters are consistent with old (15 Gyr) SSPs with a large spread in metallicity. However, in the SED of some peculiar objects there are hints for an UV upturn shortward of 2500 Å, not observed in the Galactic clusters, that could barely be explained in terms of an old SSP evolutionary scenario alone (Bohlin et al. 1993). Moreover, also a difference in the strength of some spectral features in the integrated spectra, like $H\beta$ and CN, (Burstein et al. 1984) seem to point to a differentiated evolutionary history in M 31 with respect to the Galaxy (Buzzoni et al. 1993).

A comparison of the Galactic and M 31 samples in the UBV plane (cf. Fig. 5 and Figs. 8-10) supports a substantially similar evolutionary scenario. In particular, both the Burstein et al. (1984) and Reed et al. (1992) samples closely match the fiducial theoretical locus as for the Galactic GCs. Regarding the Elson & Walterbos (1988) sample, a cross analysis of the objects in common with Reed et al. (1992) (40 clusters) and Burstein et al. (1984) (17 clusters) shows that its slightly bluer colours (about 0.05 mag in $B-V$, cf. Fig. 9) are totally accounted for by a different zero-point in the colours, a feature not surprising given the nature forcedly more heterogeneous of the Elson & Walterbos (1988) sample.

A further result of this combined analysis is that the apparent larger scatter in the two-colour diagrams of all of the M 31 samples when compared with the Galactic sample could be entirely accounted for by internal uncertainties in the observational samples turning to be about $\sigma = 0.05$ mag for both $U-B$ and $B-V$ (cf. also Bònoli et al. 1987 for a discussion).

The infrared properties of the M 31 and Galactic globular clusters are explored in Figs. 11 and 12, respectively, by comparing the Bònoli et al. (1987) M 31 cluster sample (68 clusters) and the Burstein et al. (1984) Galactic sample (17 clusters). While a fairly good agreement with the fiducial theoretical locus appears for the Galactic globulars, the M 31 sample clearly lies above the reference sequence (mainly due to a ~ 0.15 mag bluer $V-K$), although displaying a similar slope in the $(B-V)/(V-K)$ plane.

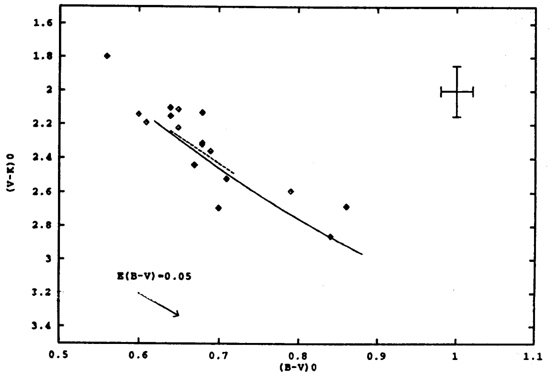

Fig. 12. Comparison between synthetic and observed indices for 17 GGCs (Burnstein et al. 1984) for an age of 15 Gyr on the plane $V-K$, $B-V$. Dotted and solid lines as in Fig. 5

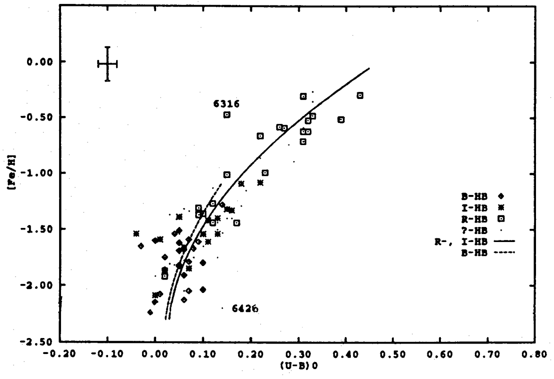

Fig. 13. Observed $U-B$ indices vs. metal content for 93 GGCs (Reed et al. 1988; Zinn & West 1984). The dotted and solid lines represent theoretical indices computed for an age of 15 *Gyr*. Symbols as in Fig. 5

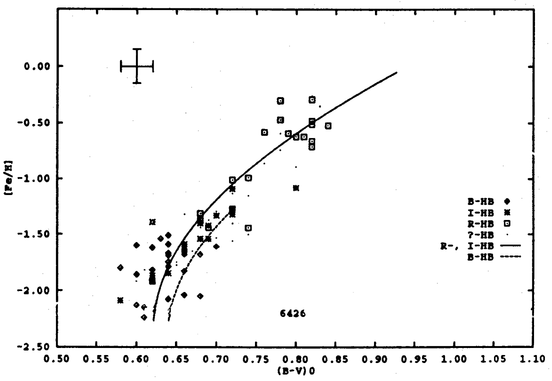

Fig. 14. Observed $B-V$ indices vs. metal content for 93 GGCs (Reed et al. 1988; Zinn & West 1984). The dotted and solid lines represent theoretical indices computed for an age of 15 *Gyr*. Symbols as in Fig. 5

On the basis of the well recognized theoretical and observational uncertainties in the infrared photometry, it is difficult to confidently assess here the problem of whether or not the M 31 and Galactic cluster populations display any intrinsic difference in their infrared properties. Discussing the original set of Aaronson's and Malkan unpublished observations for instance, Bònoli et al. (1987) do not find any significant sign against a basically homogeneous cluster population in M 31 and in the Galaxy. It is worth stressing however, that in any case we cannot have definitive arguments ruling out any possible difference in age or in other distinctive parameters in their stellar populations. Indeed, as we have shown in Figs. 3 and 4, any observational effect on colours should be lesser or of the same order of the observational uncertainties in the M 31 observations.

Turnig to the apparent discrepancy between observations and models in Fig. 11, in a conservative evolutionary scenario it could be partially recovered (without drastically disturbing the fit of Galactic clusters) by accounting for a possible systematic shift in the K synthetic magnitudes of the order of 0.06 mag and in the sense of predicting a bluer $V-K$ (cf. Buzzoni 1989). It is clear however that a further major source of uncertainty does exist to match M 31 observations. It is just the case of remind for instance the well recognized large external uncertainty of IR photometry to match the standard system.

Alternatively, if we try to recover the discrepancy in terms of different distinctive parameters of the cluster populations, an enhanced mass loss in the AGB phase would provide in our opinion the most effective tool to induce a lack of infrared luminosity without sensibly affecting the visual colours (cf. Figs. 3 and 4). If this is the real case, then an observed 0.15 mag shift in the M 31 observations would require an extremely high mass-loss rate strongly reducing (or even erasing) the AGB evolution. By the way, it is interesting to note that a deficiency in giant stars in the M 31 clusters would be expected to enhance the $H\beta$ feature in the integrated spectra of the clusters, and decrease on the contrary the CN blend, as supported by the observations (Burstein et al. 1984).

4.3. Matching the metallicity scale

A final relevant test based on the observational data includes a comparison of the [Fe/H] scale as derived from different broad-band colours. In Figs. 13 and 14, respectively, $U-B$ and $B-V$ are plotted versus Zinn's & West's (1984) metallicity, and compared with the fiducial reference locus for 15 Gyr Salpeter SSPs.

Once the effect of the different HB morphology with varying metallicity is accounted for, a pretty good match is obtained both for Reed's et al. (1988) $U-B$ and $B-V$, reinforcing the results emerging also from the calibration of narrow-band spectral indices like Mg_2 (Buzzoni et al. 1992).

A less reliable match appears however when considering the data for a low-metallicity in the plane $V-K/[Fe/H]$ shown in Fig. 15. Here, the synthetic indices are about 0.2 mag redder than the IR photometry of Brodie & Huchra (1990) at fixed metallicity. The problem might deal in part with the infrared colour shift discussed in the previous section for M 31 clusters, but a more accurate analysis of the Brodie & Huchra (1990) sample reveals however that their photometry tends systemat-

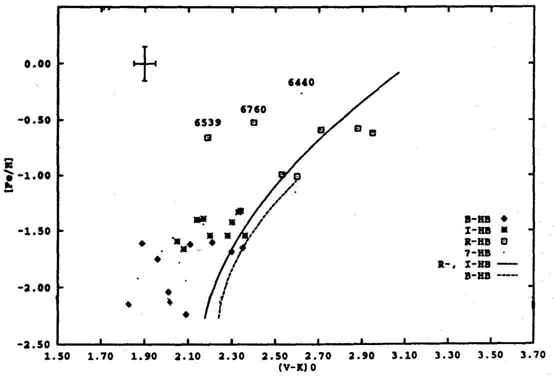

Fig. 15. Observed $V - K$ indices for 37 GGCs (Brodie & Huchra 1990) vs. metal content (Zinn & West 1984). The dotted and solid lines represent theoretical indices computed for an age of 15 *Gyr*. Symbols as in Fig. 5

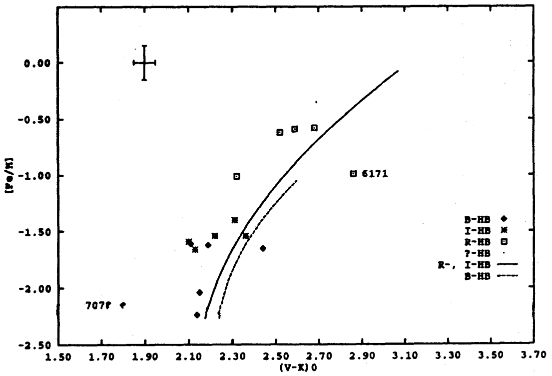

Fig. 16. Observed $V - K$ indices for 17 GGCs (Burstein et al. 1984) vs. metal content (Zinn & West 1984). The dotted and solid lines represent theoretical indices computed for an age of 15 *Gyr*. Symbols as in Fig. 5

ically to be too blue (in any of the colours) when compared with other current sources of data. The net result would lead therefore to a lower colour-inferred metallicity. Once accounting for the 0.06 mag uncertainty in the synthetic K magnitudes, things might be slightly better on the contrary when considering Frogel's et al. (1978) or Burstein's et al. (1984) photometry as shown in Fig. 16. In this case the exceedingly blue population about $[Fe/H] \sim -1.5$ disappears.

5. Conclusions

As a first step, the rôle of the physical input parameters on the derived SEDs was considered. As expected, the influence of mass loss and IMF, when considered separately, introduces only a second order effect on colours such as $U - B$ and $B - V$ with respect to the metallicity. The general trend is in the sense of obtaining slightly redder colours by decreasing mass loss or by adopting a steeper IMF.

The model predictions were compared with the observational data in two-colours diagrams referring to the various photometric systems for Galactic globular clusters and to $UBVK$ only for M 31. A general agreement is achieved between observations and models assuming 15 Gyr SSPs with a Salpeter IMF, an enhanced mass-loss rate ($\eta \sim 0.5$), and a differentiate HB morphology according to [Fe/H]. In particular, for $[Fe/H] \leq 1.5$, B- and I-HB models provide an excellent fit to the data. The agreement between computed and observed colours is rather satisfactory in the plane of $u - g$ vs. $v - g$ of Thuan & Gunn photometry and in the $M - T_1$ vs. $T_1 - T_2$ of the Washington system. The clusters found in a position discrepant from the general trend are, usually, on or near the galactic disk and belong to the central region of the Galaxy.

Conclusions similar to those obtained for our Galaxy might be drawn for M 31 clusters although the current uncertainties in the ground-based photometry do not permit to firmly single out any intrinsic difference in the distinctive evolutionary parameters with respect to the Galaxy cluster population. As a notable exception, a systematic discrepancy in the $V - K$ colour between models and observations has been remarked for the M 31 clusters. This feature might be interpreted in terms of a lack of giant (AGB) stars with respect of the Galactic clusters, and could be in agreement with the observed spectral differences between the two populations.

The $U - B$ and $B - V$ indices for Galactic clusters have been plotted vs. metallicity and compared with standard models from 15 Gyr Salpeter SSPs. Once the effect of the different HB morphologies with varying metallicity is accounted for, a pretty good match is obtained. A less reliable agreement appears, however, when considering infrared colours due in part to a less confident match between synthetic and observed K standard system.

Acknowledgements. This study has been supported by Ministero dell'Università e della Ricerca Scientifica e Tecnologica. MLM gratefully acknowledges also support from a bilateral CNR grant. SC grateful thanks the Osservatorio Astronomico di Brera for the hospitality and facilities allowed during this research.

References

Alcaino, G., 1979, Vistas in Astron., 23, 1.
Bell, R.A., Gustafsson, B., 1978, A&AS, 34, 229.
Bohlin, R.C, Deutsch, E.W., McQuade, K.A., Hill, J.K., Landsman, W.B., O'Connell, R.W., Roberts, M.S., Smith, A.M. & Stecher, T.P., 1993, ApJ, *in press*
Bònoli, F., Delpino, F., Federici, F., & Fusi Pecci, F., 1987, A&A, 185, 25.
Brodie, J.P., Huchra, J.P., 1990, ApJ, 362, 503.
Burstein, D., Faber, S. M., Gastell, C.M. & Krumm, N., 1984, ApJ, 287, 586.
Buser, R., 1978, A&A, 62, 411.
Buzzoni, A., 1989, ApJS, 71, 817 (B89).
Buzzoni, A., 1993, ApJ submitted
Buzzoni, A., Gariboldi, G., Mantegazza, L., 1992, AJ, 102. 1814
Buzzoni, A., Mantegazza, L., Gariboldi, G., 1993, AJ, in press
Canterna, R., 1976, AJ, 81, 228.
Chiosi, C., Bertelli, G., Bressan, A., 1992, ARA&A, 30, 235
Covino, S., Pasinetti Fracassini L.E., 1993, A&A, 270, 83.

Di Toma, G. 1989, Graduation Thesis, Dipartimento di Fisica, Universitá degli Studi di Milano.
Elson, R.A.W., Walterbos, R.A.M., 1988, ApJ, 333, 594.
Frogel, S.A., Persson, S.E., Aaronson, M., Matthews, K.,1978, ApJ, 220, 75.
Gingold, R.A., 1974, ApJ, 193, 177.
Gingold, R.A., 1976, ApJ, 204, 116.
Harris, H.C., Canterna, R., 1977, AJ, 82, 798.
Harris, W.E., Racine, R., 1979, ARA&A, 17, 241.
Hayes, D.S., Latham, D.W., 1975, ApJ, 197, 593.
Hayes, D.S., 1985, in Calibration of Fundamental Stellar Quantities, IAU Symp. n. 111, eds. D.S. Hayes, L.E. Pasinetti & A.G.D. Philip, Reidel Publ. Co. Dordrecht, p. 225.
Hesser, J.E., Shawl, S.J., 1985, PASP, 97, 465.
Hesser, J.E., 1993, in The Globular Clusters-Galaxy Connection, ASp Conf. Ser 48, ed(s). Smith, G.H. & Brodie, J.P., 1
Hill, S.K., Gessner, S.E., Bohlin, M.C., Cheng, K.P., Hintren, P.M., O'Connell, R.W., Roberts, M.S., Smith, A.M., Smith, E.P. & Stecher, T.P., 1993, ApJ, 402, 45.
Iben, I., Jr, 1982, ApJ, 260, 821.
Iben, I., & Renzini, A., 1983, ARA&A, 21, 271.
Kent, S.M., 1985, PASP, 97, 165.
Kukarkin, B.V., 1974, Gen. Cat. Globular Clusters, Nauka, Moscow.
Kurucz, R.L., 1979, ApJS, 40, 1 (K79).
Kurucz, R.L., 1992, in The stellar populations of galaxies, IAU Symp. no.149, eds. B. Barbuy, A. Renzini, Dordrecht, Kluwer, 225 (K92).
Oke, J.B., Gunn, J.E., 1983, ApJ, 226, 713.
Paczynski, B., 1970, Acta Astron., 20, 47.
Paczynski, B., 1971, Acta Astron., 21, 47.
Paczynski, B., 1975, ApJ, 202, 558.
Reed, B.C., 1985, PASP, 97, 120.
Reed, B.C., Hesser, J.E., Shawl, S.J., 1988, PASP, 100, 545.
Reed, G.R., Harris, G.L.H., Harris, W.E., 1992, AJ, 103, 824.
Renzini, A. & Fusi Pecci, F., 1988, ARA&A, 26, 199.
Seidel, E., Demarque, P., Weinberg, D., 1987, ApJS, 63, 917.
Reimers, D., 1975, Mem. Soc. Roy. Sci, Liége, 6th Series, 369.
Straizys, V., 1982, Ap&SS, 81, 179.
Straizys, V., Sviderskiene, Z., 1972, Vilnius Astron. Obs., 35, 1.
Sweigart, A.V., 1987, ApJS, 65, 95.
Sweigart, A.V., Gross, P.G., 1976, ApJS, 32, 367.
Sweigart, A.V., Gross, P.G., 1978, ApJS, 36, 405.
Thuan, T.X., Gunn, J.E., 1976, PASP, 88, 543.
Vandenberg, D.A., 1983, ApJS, 51, 29.
Vandenberg, D.A., 1985, ApJS, 58, 711.
Vandenberg, D.A., Hartwick, F.D.A., Alesander, D.E., 1983, ApJ, 266, 747.
Vandenberg, D.A., Bell, R.A., 1985, ApJS, 58, 561.
Vandenberg, D.A., Laskarides, P.G., 1987, ApJS, 64, 103.
Zinn, R., 1980, ApJS, 42, 19 (a).
Zinn, R., 1980, ApJ, 241, 602 (b).
Zinn, R., West, M.J., 1984, ApJS, 55, 45.

This article was processed by the author using Springer-Verlag LaTeX A&A style file version 3.