Old metal-rich globular cluster populations: Peak color and peak metallicity trends with mass of host spheroids

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Abstract. We address the problem of the factors contributing to a peak color trend of old metal-rich globular cluster (MRGC) populations with mass of their hosts, early-type galaxies and spheroidal subsystems of spiral ones (spheroids). The color-mass trend is often converted to a metallicity-mass trend under the assumption that age effects are small or negligible. While direct estimates of the ages of MRGC populations neither can rule out nor reliably support the populations’ age trend, key data on timing of the formation of spheroids and other indirect evidence imply it in the sense: the more massive spheroid the older on average its MRGC population. We show that the contribution of an allowable age trend of the MRGC populations to their peak color trend can achieve up to \( \sim 50\% \) or so. In this event the comparable value of the color trend, \( \sim 30\% \), is due to alpha-element ratio systematic variations of the order of \( \Delta [\alpha/Fe] \approx 0.1 \) to 0.2 dex because of a correlation between the \([\alpha/Fe]\) ratios and age. Hence a systematic variation of exactly \([Fe/H]\) ratios may turn out to be less significant among the contributors, and its range many times lower, i.e. of the order of \( \Delta [Fe/H] \sim 0.1 \) or even none, than the corresponding range deduced by assuming no age trend.

Key words: galaxies: star clusters – galaxies: formation – galaxies: evolution

1. Introduction

Knowledge of the basic characteristics of old globular cluster (GC) populations in spheroidal subsystems of spiral galaxies and in early-type galaxies (thereafter spheroids) of wide range of their mass is important for adequate understanding of early galactic history as well as of processes (factors) responsible for the formation of the populations. Among these characteristics, such as kinematic, spatial distribution and age, are peak metallicities of the GC populations. They provide us with valuable information on the relationships between the formation of the populations, on the one hand, and star formation (SF) in galaxies and chemical enrichment processes in them, on the other hand. In spite of essential progress achieved for the past decade in obtaining new significant data and in studying these relationships, some details remain unclear or do not receive sufficient attention. Among them seem to be those related to the dependence of metallicity of the old GC populations on mass of parent spheroids.

The majority of spheroids are known to have formed two populations of old GCs, metal-poor (MP) and metal-rich (MR) ones. While the MPGCs are virtually ubiquitous in spheroids of nearly any mass (except for least massive dwarf spheroidal galaxies), the MRGCs are, as a rule, systematically very scanty or absent at all among the least massive hosts, and the MRGCs-to-MPGCs ratio increases systematically with increasing mass of the host spheroids (Peng et al. 2006). The bimodal nature of the metallicity distribution of the old GCs in galaxies is primarily reflected in the respective bimodality of the clusters’ color distribution exhibiting two more or less distinct peaks. Transformations from colors of GCs to their metallicities are based on a number of currently available color-metallicity relations. These relations have been obtained by different groups relying on most reliable data on metallicities and colors, namely the \((V-I)\) and \((g-z)\) ones of the Galactic GCs and their extragalactic counterparts (e.g., Kissler-Patig et al. 1998; Kundu & Whitmore 1998; Peng et al. 2006). Note that the MPGCs are beyond the scope of the present paper which is devoted to old MRGC populations and to problems related to their peak metallicities and mean ages.

Peak colors of MRGC populations are in turn observed to correlate with mass (luminosity, velocity dispersion) of par-
ent spheroids, in the sense: the more massive spheroid, the redder peak color of its MRGC population (Forbes & Forte 2001; Larsen et al. 2001; Kundu & Whitmore 2001; Peng et al. 2006; among others). Although the MPGCs are not discussed here, it is useful to note that they also exhibit a peak color-luminosity trend similar to but less significant than that observed for the MRGCs (e.g., Larsen et al. 2001; Strader et al. 2006; Peng et al. 2006). At first glance, these color variations seem to be of the same nature as the bimodality of old GC color distribution, i.e. mainly or fully due to the respective metallicity variations. Currently available color-metallicity relations used for the corresponding transformations assume MRGC populations in spheroids of different mass to be more or less coeval, with no (essential) trend of their age with parent galaxy mass. This approximation is due to (1) the lack of firm direct evidence for the dependence of the ages of MRGC populations on galaxy mass, and (2) the lack of suitable empirical calibrators of the color-metallicity relation for other than old ages. However, it is clear that it is only first approximation to the problem under consideration. Resolving it can have a number of important consequences, particularly for adequate understanding of the formation of MRGCs. Here, we address the problem of the age trend among MRGC populations by relying principally on an available body of indirect evidence. Hence we attempt to estimate plausible constraints that may be imposed on the contribution of metallicity to a color trend. Also, we briefly discuss their implications for the MRGC formation.

In Sect. 2 we briefly summarize the basic results on timing of the formation of spheroids, obtained from studies of both high redshift galaxies and nearby ones. The conservative upper limit of possible systematic age difference between MRGC populations in spheroids of different mass is considered in Sect. 3. Its contribution to a peak color trend of MRGC populations with mass of the host spheroids is estimated in Sect. 4. Sect. 5 contains summary and concluding remarks.

2. Timing of the formation of spheroids

The key results obtained to date on early stages and timing of the formation and evolution of spheroids provide a valuable observational information for more adequate understanding of the same aspects concerning old MRGC populations.

Approximately linear relation between masses of supermassive black holes (SBHs) and host stellar bulges (Magorrian et al. 1998; Gebhardt et al. 2000; Graham et al. 2001) implies that the formation of these components of spheroids must be related and that the growth of SBHs and massive bulges occurred simultaneously. Therefore, the bulk of stars in spheroids formed at the same time as their SBHs acquired most of their mass (e.g., Page et al. 2001; Granato et al. 2001; Shields et al. 2003). SF activity and its respective impact on accretion onto the SMBs in early spheroids are tightly bound to the basic characteristics of high redshift QSOs, as well as to the properties of the QSO luminosity function and its redshift evolution. Haiman, Ciotti & Ostriker (2004) argue that the redshift evolution of the QSO emissivity and of the SF history in spheroids should be approximately parallel. According to Granato et al. (2001), the evolution of QSOs and galaxies can be well understood if we accept that spheroids of different mass form the bulk of their stars on different timescales: the more massive spheroid (and its SBH), the shorter timescale. Recent observations are in good agreement with this conclusion. Correlations have been found between velocity dispersion and age (e.g., Caldwell, Rose & Concanon 2003), between [$\alpha$/Fe] and velocity dispersion, as well as between the alpha-element abundance ratios and mean ages (Thomas, Maraston & Bender 2002) of early-type galaxies. Hence one deduces that more massive galaxies had shorter timescales of their star formation. Indeed, data on high redshift objects, around $z \sim 6$, reveal the very massive SBHs and galaxies with high SF rate to form in the early Universe (Bertoldi & Cox 2002; Bunker et al. 2003; Willott, Mcure & Jarvis 2003; Freudling, Corbin & Korista 2003). At the same time, the timescales may differ, to a certain extent, for galaxies of the same mass forming in high and low density environments (Thomas et al. 2005).

The deduced timescale of the formation of the bulk of stars in the most massive spheroids, with velocity dispersion around or exceeding $\sigma \approx 300$ km s$^{-1}$, is short as compared to a Hubble time. In the above-cited publications as well as in a number of other ones devoted to the formation of high redshift galaxies, the timescale is estimated to be of order or even less than 1 Gyr since the Big Bang. In turn, spheroids of systematically lower mass achieve the epochs of their highest SF rate systematically later. According to the estimates by Thomas et al. (2002), for example, an age difference between these epochs in the very massive spheroids and in those with $\sigma \approx 80$ km s$^{-1}$ is around 10 Gyr.

It has to be noted, however, that the ages under consideration, i.e. ones estimated for stellar populations confined in spheroids, are often luminosity weighted. They can significantly be affected by stars formed in last essential burst of star formation in a galaxy rather than by the bulk of the galaxy’s populations formed (much) earlier.

3. Implied age difference between MRGC populations in spheroids of different mass

Observations of galaxies in the nearby Universe unambiguously reveal a tight relationship between high SF rate and formation of as massive star clusters as GCs (e.g., Larsen & Richtler 2000; Larsen 2000, 2002). Similarly, evidence for the formation of both MRGCs and metal-rich stars in early spheroids in the same star formation events, with similar ages and metallicities has been presented by Harris, Harris & Poole (1999), Durrell, Harris & Pritchet (2001), Forbes & Forte (2001) and Forbes (2002).

The estimated epochs of the highest SF activity in spheroids of wide mass range imply that the bulk of MRGCs populating the most massive of the hosts are very old and nearly coeval with MPGCs because their mean age difference is expected to fall between a few hundred Myr and 1 Gyr. Moreover, MRGC populations in lower mass hosts are likely systematically younger than in the higher mass ones,
similarly to the hosts’ field stars. In other words, the conclusions achieved to date on the timescale of the formation of spheroids with different mass provide important implication for the MRGCs populating the hosts: the more massive spheroid (or the higher its velocity dispersion), the older on average its MRGC population. At the same time, it cannot be excluded that GCs may be somewhat older than the field stellar populations in the same elliptical galaxies (Puzia, Kissler-Patig & Gougfrooij 2006). In other words, age trends of MRGCs and of the corresponding metal-rich field stellar populations may be somewhat different.

Due to their limited accuracy of a few Gyr at best, the direct estimates of the ages of MRGCs in spheroids of different mass neither can rule out such an age trend nor reliably support it at least within 4-6 Gyr since the Big Bang. As a rule, such estimates are made for the MRGCs belonging to spheroids of higher mass, with stellar mass $M_* > 10^{10} M_\odot$, in which the clusters can be isolated in sufficient number (tens). The MRGC populations are typically concluded to be either older than 8-10 Gyr or as old as MPGCs (see, for example, Puzia et al. 1999; Larsen et al. 2002; Puzia et al. 2002; Beasley et al. 2004; Strader et al. 2005; Pierce et al. 2006). It is now difficult to reliably conclude on such a trend and on its value. However, its conservative upper limit of ~5 Gyr, corresponding to the mentioned uncertainty of MRGC ages in spheroids with stellar mass $M_* > 10^{10} M_\odot$, seems to be quite realistic. Indeed, Puzia et al. (2005) estimate that up to one third of GCs in early-type galaxies have ages in the range 5-10 Gyr. It has to be noted, however, that this result is based on very limited sample of GCs, and it is not clear whether there is any trend of mean age of the MRGCs with galaxy mass. Among other data that might count in favor of such a trend we refer to those obtained recently on GCs in the giant elliptical galaxy M87, on the one hand, and in dwarf ellipticals, satellites of the Andromeda galaxy, on the other hand. Sharina, Afanasiev & Puzia (2006) find three MRGCs (([Z/H] ≥ −0.8 dex) in NGC 185 and NGC 205. All of them are of apparently younger ages (≤ 7 Gyr) than their Galactic counterparts. In turn Sohn et al. (2006) have found that GCs in M87 are notably bluer in the (FUV − V) color than those in the Galaxy, including MRGCs. Older ages of GCs in M87 is one of the basic factors that can be responsible for this color difference.

It is worth of noting that the difference in the slopes of the color-metallicity relations (namely in their metal-rich range) obtained by Kundu & Whitmore (1998) and Kissler-Patig et al. (1998) relying on the data on GCs of the Milky Way and the cD galaxy NGC 1399, respectively, is in agreement with older ages of the MRGCs belonging to NGC 1399. It is interesting that the peak metallicity deduced from peak color of the MRGCs in NGC 1399, using just the latter color-metallicity relation based on spectroscopy of a sub-sample of the MRGCs from the same galaxy, is [Fe/H] = −0.6. The same relation gives [Fe/H] = −0.5 for MRGCs of another very massive galaxy, the giant elliptical M87 (Kissler-Patig et al. 1998). By calibrating the $(B − V)$ colors of GCs in the spiral galaxy M81 with spectroscopically based metallicities of a sub-sample of the galaxy’s clusters, Ma et al. (2005) obtain [Fe/H] = −0.53 for the M81 MRGC population. Therefore, these peak values of [Fe/H] are indistinguishable within the errors from each other and from peak metallicity of the Galactic MRGCs. In other words, in the case when peak metallicities of MRGC populations, belonging to galaxies of different mass, are derived either from spectroscopy or from spectroscopically based color-metallicity relations obtained for the same parent galaxies, the deduced peak values of [Fe/H] converge. Moreover, the difference between these peak values becomes smaller as compared to that derived only from peak colors by means of any single color-metallicity relation.

4. Effect of an age trend on the deduced variation of peak metallicity

To estimate a contribution of the assumed age trend to color trend of MRGC populations and consequently the deduced variation of peak metallicity, we combine (1) color-metallicity relations for appropriate ages, based on evolutionary population synthesis models, with (2) observational data on real color range corresponding to systematic spread of peak colors of MRGC populations belonging to spheroids of the mass range under consideration. For this purpose we used the latest data of Peng et al. (2006) on the dependence of the $(g − z)$ peak colors of the MRGC populations on luminosity (stellar mass) of their parent early-type galaxies belonging to the Virgo cluster. For galaxies with stellar mass $M_* > 10^{10} M_\odot$, peak colors of their MRGC populations are found to fall between $1.2 \leq (g − z) \leq 1.4$. 

Fig. 1. The effect of possible systematic age difference among MRGC populations belonging to spheroids of different mass on a trend of their $[Z/H]$ peak metallicity as a function of their $(g − z)$ peak color; color-metallicity relations for ages of 9 Gyr and 14 Gyr are shown by long-dashed line and dash-dotted line, respectively, using evolutionary population synthesis models by Maraston (2005); for more details and explanations see the text.
Fig. 1 demonstrates the effect of possible systematic age difference among MRGC populations on a deduced trend of their [Z/H] peak metallicity as a function of their $(g - z)$ peak color. In order to estimate the effect, one of the currently available sets of evolutionary population synthesis models is used. Specifically, we rely on recently developed models by Maraston (2005). Presented are those of them whose age differs by 5 Gyr, namely models with age of 9 Gyr and 14 Gyr, and in the metallicity range under consideration. In Fig. 1 they are connected by long-dashed line and dash-dotted line, respectively. These are models with Salpeter initial mass function and with blue horizontal branch at the two lowest metallicities, [Z/H]$=−2.25$ and [Z/H]$=−1.35$. The color range of $\Delta(g − z)$=0.2 mag is translated to metallicity range of $\Delta[Z/H]_{\text{peak}}$ $\approx$ 0.5 dex if color-metallicity relation of the same age is used: in our example it corresponds to the models with age of 9 Gyr (long-dashed line). Note that approximately the same metallicity range, but at somewhat lower mean metallicity, is deduced using models with age of 14 Gyr (dash-dotted line). However, twice as lower metallicity range of peak metallicities, $\Delta[Z/H]_{\text{peak}}$ $\approx$ 0.25 dex, would be deduced if the MRGC populations having the color $(g − z)$=1.2 and belonging to the lower-mass galaxies ($M_\star \approx 10^{10}M_\odot$) were 9 Gyr old whereas their counterparts populating galaxies of highest mass and exhibiting redder peak color, $(g − z)$=1.4, were 5 Gyr older. It is evident that at a given metallicity, say [Z/H]/$\approx$ $-0.3$ to $-0.4$ dex, according to the models used, the effect of the discussed age difference among MRGC populations in galaxies of different mass may achieve around 0.12 mag in the color $(g − z)$.

Virtually the same is valid regarding a trend of the $(V − I)$ color. We mention here the results of Larsen et al. (2001) obtained from a quite large homogeneous set of data on GCs in early-type galaxies spanning ranges of absolute $B$-magnitude, $M_B$, and central: $\Delta M_B \approx 3.5$ mag and $\Delta \log \sigma \approx 0.6$ dex, respectively. These variations of the galaxy characteristics approximately correspond to the above-considered range of galaxy mass. The least-squares fits to the data plotted as relations between $(V − I)$ peak colors of MRGC populations and $M_B$ or $\log \sigma$ show the difference of $\Delta(V − I) \approx 0.08$-0.10 mag corresponding to the given ranges of the galaxy characteristics. Similarly, approximately 4 − 5 Gyr of the systematic age difference among MRGC populations belonging to spheroids of the mentioned mass range can account for around 50% of the color trend.

It has to be noted that in the case of an age trend of MRGC populations (in galaxies with $M_\star > 10^{10}M_\odot$) of the order of 5 Gyr or more, it is a trend of their [$\alpha$/Fe] ratios with age that may be the mainly or even the only responsible for the peak metallicity trend that corresponds to the rest of peak color trend (after taking into account the effect of age). Indeed, by analyzing [$\alpha$/Fe], metallicity, and age distributions of GCs in elliptical, lenticular, and spiral galaxies, Puzia et al. (2006) find (tentative) evidence for an age−[$\alpha$/Fe] correlation for GCs at least in elliptical galaxies. This correlation is expressed in increasing values of [$\alpha$/Fe] ratios with age of GCs. By relying on these data we estimate that the ratios may change by at least $\Delta[\alpha/Fe]$ $\sim$ 0.1 − 0.2 dex for the accepted period of 5 Gyr. For definiteness we accept 0.15 dex. From relation between total metallicity, [Z/H], and its constituents, [Fe/H] and [$\alpha$/Fe] (namely [Fe/H] = [Z/H] − 0.94[$\alpha$/Fe]; Thomas, Maraston & Bender 2003), a trend of exactly [Fe/H] peak values of MRGC populations with mass of their hosts is of the order of $\Delta[\text{Fe/H}] \sim$ 0.1 dex (using $\Delta[Z/H]_{\text{peak}} \approx$ 0.25 dex or smaller.

One caveat about the estimates made above from the model relations is that any such a relation (for a given age) between the color $(g − z)$ and metallicity, [Z/H], is assumed to be the same for different metal mixture (i.e., of [Fe/H] and [$\alpha$/Fe] ratios) for any [Z/H]. However, the situation may be more complicated as discussed recently by Salaris & Cassisi (2007) for other broad-band colors. It is not clear (1) what an order of magnitude of possible color difference may be just in the color $(g − z)$ for various metal mixture at the same metallicity [Z/H], and (2) how such a color difference depends on metallicity at a given age. Hence it is difficult to adequately take into account such effects (if any) in the present study.

Therefore, there are two principal alternatives. First one is the case of no age trend among MRGC populations belonging to spheroids of different mass. It assumes only one factor, [Fe/H] trend, responsible for a peak color trend of the populations with galaxy mass. Second one, corresponding to the case of age trend, implies three contributors to the color trend: age, [$\alpha$/Fe] and [Fe/H] systematic variations. As we show above, the color trend is likely caused by a number of factors rather than by the only variation of iron abundance. Up to $\sim$50% of this trend may be due to an age trend of the MRGC populations. In this event $\sim$30% of the peak color trend originate from systematic variation of alpha-element abundance ratio, and the rest ($\sim$20%) from variation of exactly [Fe/H] ratios.

5. Summary and concluding remarks

By summarizing and analyzing the results available on MRGC populations and on their parent galaxies, we conclude the following. On the one hand, the strong evidence is provided for the dependence of peak color of the populations on mass (velocity dispersion) of their hosts. On the other hand, it is now definitely unknown which of the factors, metallicity or age trend, contributes more to this dependence. The latter is assumed to be small or negligible as compared to the former one. Strictly speaking, there is only one more or less reliable constraint on age of MRGC populations belonging to spheroids with mass $M_\star > 10^{10}M_\odot$. Specifically, the populations are found to be typically older than 8-10 Gyr. That is, they are old with uncertainty of $\sim$ 4-6 Gyr. However, as we demonstrate and argue here, there is no observational reason to neglect systematic age variations among MRGC populations within this age range. On the contrary, from indirect evidence the existence of a trend of age of the populations with galaxy mass is rather more probable than its absence. The contribution of such an age trend to the populations’ color trend can be comparable to the contribution of metallicity trend. Therefore, the assumption that age effects are
small or negligible, and the enforced conversion of a color-
mass trend to a metallicity-mass trend may ultimately lead
either to inadequate conclusions on the processes responsible
for the formation of MRGCs or to overestimating role
of some of these processes and missing role of other ones.
For this reason we estimate possible systematic age variation
between MRGC populations belonging to spheroids in mass
range of nearly two order of magnitude. Furthermore, by re-
lying on currently available observational data and models,
we evaluate an order of magnitude of the respective effect of
the MRGC populations’ age trend on the deduced trend of
their peak metallicity with mass of their hosts. We also show
that in the case of such an age trend, the real systematic vari-
ation of total metallicity, [Z/H], of the populations is presumably
mainly due to an age−[α/Fe] correlation among GCs.
Hence systematic variation of exactly [Fe/H] ratios, another
constituent of the total metallicity, is smaller or even none.

We have recently argued (Kravtsov 2006) that the forma-
tion of both the old MRGCs in spheroids and young/intermediate-age massive star clusters in irregulars, as well as increased SF activity accompanying the formation of the clusters, occur at (approximately) the same stage of the host galaxies’ chemical evolution. These processes achieve their maximum around [Fe/H] ∼ −0.5 dex (Z ∼ Z⊙/3). Here we show that real range of systematic metallicity spread, particularly expressed in [Fe/H], of MRGC populations is likely more limited than the metallicity range usually deduced from the populations’ peak color variation. The latter range is probably the upper limit and is related to the total metallicity, [Z/H], rather than to [Fe/H]. It can fully be attributed to [Fe/H] only provided that there is insignificant or no age trend of the populations, as already mentioned above.

It would be useful to compare the metallicity range de-
duced from the discussed color trend of MRGCs with those
obtained using other methods that are more capable to disen-
tangle age and metallicity effects. In particular, most reliable
spectroscopic metallicity estimates for the MRGCs belong-
ing to (the same) galaxies at two extremes of their mass range
could presumably allow one to impose more strict constraints
on the metallicity trend (and therefore on the age trend) of the
MRGC populations. Other alternative might be the use of dif-
ferent colors which are more sensitive to metallicity and less
sensitive to age, such as V − K, B − K, etc.

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