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On the bimodal color distribution of Globular Cluster systems

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Abstract. The study of globular cluster (GC) systems in galaxies is one of the keystones to understand the physical processes at the base of the formation and evolution of galaxies. One of the most intriguing properties of GC systems in early-type galaxies is their bimodal color distributions, i.e. the presence of two well separated peaks in the color histograms. In general, color bimodality is equated to metallicity bimodality, thus GC formation models adopt different mechanisms/periods of formation for the two discrete GC sub-populations. Several models have been proposed to explain the observed color bimodality in terms of metallicity bimodality. However, recently it has been shown that color bimodality is not necessarily due to a bimodal metallicity distribution, and that it may be a consequence of nonlinear color-metallicity relations. If that's the case, there is no need to invoke the coexistence of two discrete GC sub-systems. After a brief introduction to GC color bimodality and to the formation scenarios proposed, we present some results showing that unimodal metallicity distributions might be "projected" into bimodal colors due to the non-trivial role played by non-linear color-metallicity relations.

Key words. Stars: Population II – Galaxies: star clusters: general – Galaxies: fundamental parameters

1. Introduction

The study of star clusters in galaxies provides an accurate and relatively straightforward tool to unveil the mechanisms that produced the present organization and evolutionary properties of stars in the galaxy. Among star clusters, Globular Clusters (GCs hereafter) play a fundamental role for extragalactic Astronomy, mainly because (*i*) they are recognizable out to very large distances (beyond $\sim$ 100 Mpc, e.g. Maybhate et al. 2009) especially in early-type galaxies where the GCs can be easily recognized against the smooth luminosity profile of the host galaxy, and (*ii*) to a good approximation they host a simple stellar population (SSP, single age and single $[Fe/H]$ stellar system), thus their properties can be constrained by direct comparison to SSP models, without the difficulties involved with field stars where a complex star formation history further complicates the interpretation of observations. Moreover, it is well accepted that, in regular galaxies, GCs have a relatively uniform old age, and show a spread in metallicity (e.g.

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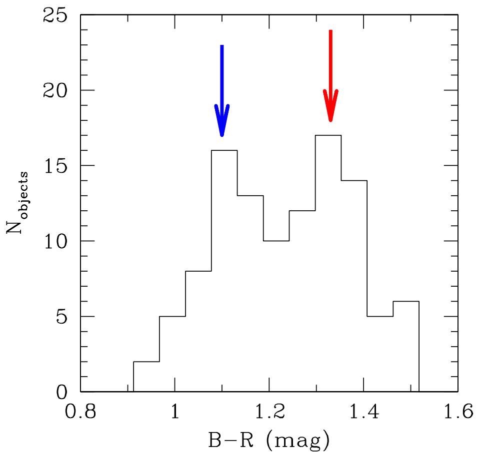

Fig. 1. Color histogram of the GC system in the S0 galaxy NGC 5866, based on ACS/HST data. The plotted data refer to a sample of 109 GC candidates selected on the base on their color and shape (Cantiello et al. 2007). The GC system is "normal" in all analyzed features (GC luminosity function, specific frequency S_N, color distributions, etc.), in the figure the estimated position of blue and red peaks are also shown with blue and red arrows, respectively.

Hempel et al. 2007). For a fairly detailed review on extragalactic GCs properties and their link to galaxy formation see Brodie & Strader (2006).

2. Bimodal color, bimodal $[Fe/H]$?

2.1. Fast facts

One of the most intriguing features of the GC systems in normal ellipticals is the bimodal distribution of colors. An example of such feature is whown in Figure 1. The bimodal color distribution is a common feature in GC systems, and it is widely accepted that it *"is due principally to a metallicity difference between two old subpopulations"* Brodie & Strader (2006).

The presence of two discrete GC subpopulations has been associated with the occurrence of two distinct events, or two distinct mechanisms of formation. Such events or mechanisms, in turn, must be properly accounted into realistic models of galaxy formation and evolution.

The scenarios proposed to explain the bimodal $[Fe/H]$ in terms of galaxy formation can be divided in three different classes: (*i*) the dissipative merging of dust-rich galaxies hosting blue/metal-poor GC systems, with the subsequent formation of the red/metal-rich GC sub-population (Ashman & Zepf 1992); (*ii*) the feeding of blue GCs from dwarf galaxies to massive elliptical hosting the red GCs (Cote et al. 1998); and (*iii*) *in situ* formation, with two distinct phases of formation of the GC sub-systems out of gas with different chemical composition (Forbes et al. 1997).

The main evidence in support of bimodal colors as a consequence of bimodal $[Fe/H]$ distributions comes from the metallicity distribution of Galactic GCs, which is definitely bimodal (Côté 1999). However, as testified by the various models proposed, both hierarchical and non-hierarchical galaxy formation scenarios do not naturally produce GC systems with bimodal metallicity distributions. On the contrary, the stochastic nature of galaxy formation would be expected to result in broad Gaussian-like $[Fe/H]$ distributions. Furthermore, while in cases like the Milky Way the bimodal $[Fe/H]$ could be the outcome of few discrete bursts of star formation, it is difficult to see how bimodality would be nearly universal for spheroidals over a wide range of luminosity/mass (~5 mag in M_B, Peng et al. 2006), and extremely different environments: from galaxies in compact clusters, like the case of the Fornax cluster (Mieske et al. 2010), to isolated galaxies, as NGC 5866 (Cantiello et al. 2007).

2.2. Non-linear color-metallicity relations

The underlying assumption in the equivalence between color–$[Fe/H]$ bimodality is the linearity of color-metallicity relations (CMRs), so that the shape of the $[Fe/H]$ distribution is preserved when "projected" into colors. However, there is a mounting observational and theoretical evidence that CMRs are generally non-linear. In Figure 2 we show the CMRs for two colors widely used for the study of GC systems

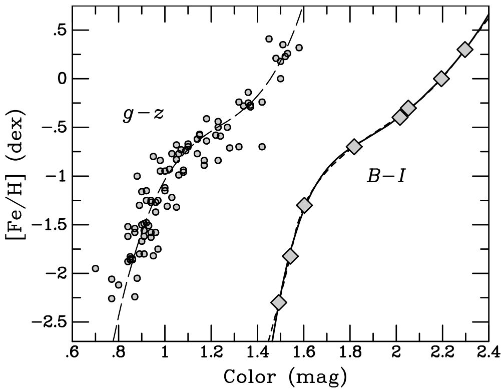

Fig. 2. Observed and theoretical CMRs for two commonly used colors (figure from Blakeslee et al. 2010). The panel clearly shows the non-linearity of CMRs, both with observational data ($g-z$ and spectroscopic $[Fe/H]$ are from Galactic GCs plus metal rich GCs in two bright Virgo ellipticals, Peng et al. 2006), and with SSP models ($B-I$ models from the SPoT group, Raimondo et al. 2005).

(e.g. Brodie & Strader 2006; Harris et al. 2006; Peng et al. 2006).

The consequence of the non-linear CMRs, and its effects on the color distribution of GC systems has been analyzed by Yoon et al. (2006), Cantiello & Blakeslee (2007), Blakeslee et al. (2010). In all cases the authors have shown that using CMRs that properly take into account the effect of non-linearity, both the observational and theoretical relations predict that a unimodal $[Fe/H]$ distribution can be projected into a bimodal color distribution. In other words, the authors conclude that *having a bimodal color distribution is a necessary but not sufficient condition for a bimodal* $[Fe/H]$ *distribution*. In addition, it has been demonstrated that there are *physically meaningful* cases where a unimodal $[Fe/H]$ distribution can show a bimodal color distribution similar to observed ones (see the quoted papers for more details).

In order to prove or disprove the possible role of non-linear CMRs on color bimodality, new/different observations are required. Here, we list three lines of evidence showing that the projection of unimodal $[Fe/H]$ into bimodal colors is effective, at least in part, and propose new observational tests useful to improve our understanding of the problem.

– As observed by Cantiello & Blakeslee (2007), although all colors are affected by some degree of non-linearity, the latter is stronger for certain couples, like $g-z$ or $V-I$, but has a significantly lower impact on optical to near−IR colors, like $V-K$. Figure 3 shows the results of a simulation where a unimodal Gaussian $[Fe/H]$ is adopted (upper left panel), with peak $[Fe/H]= -0.65$ dex and width $\sigma_{[Fe/H]} = 0.5$. The color distributions also shown in the Figure are derived using the theoretical CMRs from SPoT SSP models (Raimondo et al. 2005). The upper-right panel in the Figure is particularly interesting, as it shows that a clearly bimodal $V-I$ can be obtained even if the input $[Fe/H]$ is unimodal. On the contrary, the color distributions in the two lower panels are broad with asymmetric tails, in part reflecting the reduced impact of non-linearity for such colors. Thus, while true $[Fe/H]$ bimodality should project into bimodal colors no matter what color is observed, unimodal $[Fe/H]$ could project into bimodal/unimodal colors depending on the color analyzed and on the properties of the distribution (peak $[Fe/H]$, width, number of GCs, etc.).
In conclusion, the simulations carried out by Cantiello & Blakeslee, demonstrate that a unimodal $[Fe/H]$ is less likely projected into a bimodal $V-K$ than into a bimodal $g-z$ (see the paper for simulations with other SSP models and various $[Fe/H]$ distributions). It is interesting to note that cases like NGC 4472 show clear bimodal $V-I$ and $g-z$ colors (Larsen et al. 2001; Peng et al. 2006, respectively), but the $V-K$ is far from being definitely bimodal. However, the number of galaxies with high quality near-IR photometry for a large number of GC is still unsatisfactorily low. Next generation surveys and telescopes with new near-IR detectors will provide a large amount of data useful to solve this issue.

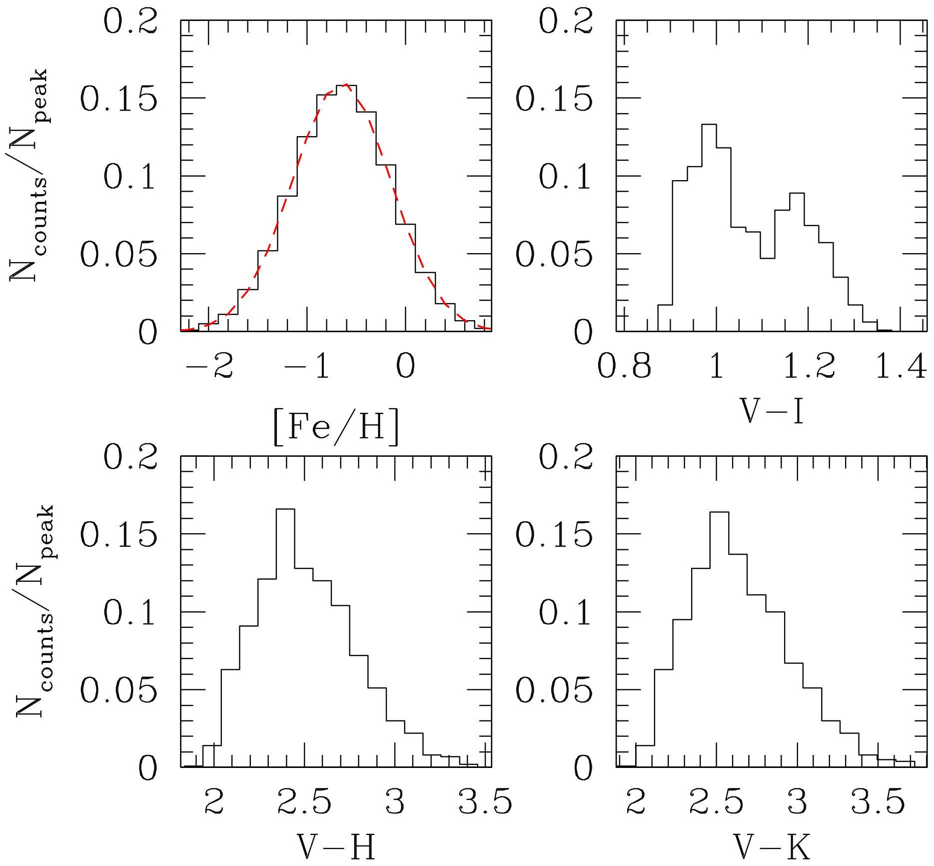

Fig. 3. A simulated unimodal $[Fe/H]$ distribution (upper left panel) and its associated color distributions obtained using the theoretical color-metallicity relations from SPoT models (see Cantiello & Blakeslee 2007, for details). The figure shows that the same $[Fe/H]$ distribution projects into a bimodal $V-I$, while the corresponding $V-H$ and $V-K$ appear more unimodal with and asymmetric tail toward red colors. All histograms are normalized to the peak value.

– Blakeslee et al. (2010) have shown that if non-linear CMRs are coupled with a self-enrichment of the most massive GC in the populations, then the recently discovered *blue tilt* observed in bright ellipticals (Harris et al. 2006) could be reproduced together with the color bimodality.
The presence of chemical anomalies and of multiple RGB or MS sequences is now observed in all massive Galactic GCs, and widely accepted as an effect of self-pollution (Renzini 2008). Moreover, the excess of far-UV flux detected for massive GC in M 87 has also been considered a possible signature of self-enrichment and would further demonstrate that this phenomenon is not limited to our own Galaxy (Kaviraj et al. 2007). Adopting accurate

CMRs, *plus* a reasonable self-enrichment of metals of GCs originated from a unimodal $[Fe/H]$ distribution, Blakeslee et al. have shown that it is possible to reproduce at the same time (*i*) the bimodal color distribution, (*ii*) the blue tilt, and (*iii*) the observed correlation between the strength of the blue tilt and galaxy luminosity.

– Foster et al. (2010) have obtained Keck/DEIMOS spectra of ∼140 GCs in the bright E0 galaxy NGC 1407. The GCs analyzed represent the largest available sample for a number of GC representative of the entire population in the galaxy. Previous spectroscopic studies, in fact, provided data for roughly ∼1% of the GC population, and were strongly biased towards bright/massive clusters. Adopting the Calcium Triplet as a $[Fe/H]$ indicator for GCs located in the blue and red peaks of the distribution, Foster et al. find that *"even though the average g−i colors are separated by over ∼0.2 mag, the Calcium Triplet line strengths of the two mean raw spectra are nearly identical suggesting similar metallicities."* In other words, the spectroscopic analysis of GCs with well separated color does not provide evidence of a significant $[Fe/H]$ spread for the two supposed GC sub-components. The authors conclude suggesting that new independent spectroscopic studies are required to give a clear answer to the questions raised from their study.

3. Conclusions

The bimodal color distribution of extragalactic GC systems is a well known feature of GC systems in spheroidals, observed over more than ∼5 mag in M_B, and for galaxies in a range of different environments. The presence of such a feature has been associated with the co-existence of two discrete GC subpopulations which originated from two different events, or according to two different mechanisms. The astrophysical consequences of a bimodal color distribution are not trivial, as they are used to constrain and evaluate various galaxy formation and evolution scenarios.

The (almost) universal assumption that bimodal colors are essentially due to a bimodality in $[Fe/H]$, is equivalent to the assumption that CMRs are linear. However, as observations of GCs and SSP models improve their accuracy, it is clear that the approximation of linearity fails, and non-linear CMRs provide better agreement between data and models.

After the works of Yoon et al. (2006) and Richtler (2006), it has been shown that color bimodality is not necessarily associated with bimodal $[Fe/H]$, on the contrary unimodal or flat $[Fe/H]$ distributions can be projected into bimodal color distributions. Whether such a projection effect plays a minor or major role in shaping the observed color distributions cannot be established with present observational datasets.

In this brief report, we have summarized the evidence in favor of a non-trivial impact of non-linear CMRs on determining the color distribution of GC systems. In this scheme a broad unimodal $[Fe/H]$ distribution – arising from the stochastic nature of galaxy formation – possibly coupled with some level of GC self-enrichment, is able to reproduce various observational properties of GC systems. A naive application of Ochkam's razor would tell us that such interpretation should be preferred to any one based on less general hypotheses. However, the observational datasets available are insufficient to allow firm conclusions. New (*i*) optical to near-IR photometric studies for large samples of galaxies spanning a wide magnitude interval, together with (*ii*) spectroscopic studies of GC statistically representative of the entire GC population in bimodal systems would provide new constraints on this topic, and on the related issues of galaxy formation and evolution.

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