Star clusters: basic galactic building blocks
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An optical/near-infrared survey of GCs in early-type galaxies

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Abstract. Optical/near-infrared observations of 14 globular cluster (GC) systems in early-type galaxies are presented. We investigate the recent claims (Yoon *et al.* 2006) of colour bimodality in GC systems being an artefact of the nonlinear colour–metallicity transformation driven by horizontal-branch morphology. Taking advantage of the fact that the combination of optical and near-infrared colours can, in principle, break the age/metallicity degeneracy we also analyse age distributions in these systems.

Keywords. galaxies: star clusters, galaxies: elliptical and lenticular, cD, galaxies: star clusters

1. Introduction

The ubiquity of globular clusters (GCs) around all major galaxies and the fact that young star clusters are being observed in many mergers and starbursts we observe today suggests that GC formation traces important star-formation events in the histories of their host galaxies (Brodie & Strader 2006).

GC systems generally exhibit a colour distribution that is bimodal (sometimes multi-modal) in optical colours. Spectroscopic studies (e.g., Strader *et al.* 2005; Cenarro *et al.* 2007) show that this bimodality is due to old subpopulations with ages greater than 10 Gyr that differ in metallicity. Bimodal metallicity distributions may indicate distinct formation mechanisms, with age differences ~ 2 Gyr still allowed within the uncertainties on current age estimates. This metallicity bi/multimodality seems to hold for the majority of galaxies, except for the low-mass galaxies which appear to have only a metal-poor GC subpopulation. Recently, Yoon *et al.* (2006) challenged this metallicity-bimodality interpretation saying that it is an artefact of horizontal-branch morphologies. These authors argue that nonlinear colour–metallicity relations may transform a unimodal metallicity distribution into a bimodal optical colour distribution. This issue has been investigated in more detail by Cantiello & Blakeslee (2007), who concluded that combinations of optical and near-infrared (NIR) colours are much less prone to this effect. Metallicity bimodality was thus contested and it is, therefore, important to investigate this topic in more detail. On the other hand, if metallicity bi/multimodality is genuine, there could be multiple episodes/mechanisms of GC formation in a galaxy with a possible age difference. It is thus equally important to study the age distributions of these systems.

It is still an open issue in the literature whether some early-type galaxies known to contain old stellar populations from integrated light studies can host a high percentage of intermediate-age (2–3 Gyr) GCs. The two strongest cases are NGC 4365 (Puzia *et al.* 2002; Larsen *et al.* 2005) and NGC 5846 (Hempel *et al.* 2003). Comparison of two-colour plots of the GC systems with simple stellar population (SSP) models (e.g., Bruzual &

Charlot 2003; Maraston 2005) suggested the presence of intermediate-age GCs in these galaxies.

With the aim of investigating ages and metallicity distributions in GC systems of early-type galaxies, we examine 14 E/S0 systems, with $(m - M) < 32$ mag and $M_B < -19$ mag using optical and NIR imaging. We obtained deep (~ 3.4 hr) K-band photometry with the LIRIS instrument on the *William Herschel Telescope* at La Palma, which has a field of view of 4.2×4.2 arcmin^2. This was combined with optical imaging extracted from the *Hubble Space Telescope* public archive in the g (F475W) and z (F850LP) bands. GC candidates were selected automatically in galaxy-subtracted images through standard routines. The following cuts were applied, defining the final sample: $g < 23$ mag, $0.5 < (g - z) < 2$ mag, effective radii $1 < R_{\rm eff} < 15$ pc and magnitude error $K_{\rm err} < 0.5$ mag. With these restrictions, typical magnitude errors for the optical g and z bands were ~ 0.05 mag. For the NIR band, the magnitude errors were measured as ~ 0.06 mag for a $K = 19$ mag GC and ~ 0.2 mag for a $K = 20$ mag GC. Artificial-star tests, however, show that the K-band magnitude errors can be underestimated by a factor of 2. In what follows, it is shown what knowledge was gained from these data regarding the age and colour (metallicity) distributions of the GC systems studied here.

2. Ages

The combination of optical/NIR imaging is an alternative to spectroscopy in age dating GCs. The technique relies on comparing two-colour diagrams with the predictions of SSP models. In Figure 1 two-colour diagrams $(g - k)$ versus $(g - z)$ for the GCs that satisfy the criteria mentioned above for the 14 galaxies are shown. In the left panel, a model grid from Maraston (2005) is overplotted with model sequences of constant age as solid lines: 2, 3, 4, 5, 6, 8, 11 and 14 Gyr. If one examines the case of NGC 4365, the galaxy that showed evidence of having intermediate-age clusters, one concludes that this galaxy is no different from any other in the sample. In the right panel, the same data as the left panel are shown, but now overplotted with Padova SSPs with Marigo *et al.* (2008) isochrones and a new treatment of the thermally pulsing asymptotic giant branch (TP–AGB) phase with the same age range as for the first panel. These latter models for old ages ($\sim 11, 14$ Gyr) are a close match to the data, while Maraston (2005) models show an offset that would imply intermediate ages ($\sim 2, 3$ Gyr). Charlot & Bruzual (in prep.) preliminary models yield basically the same conclusion as the Maraston (2005) models: the $(g - k)$ SSPs are $\sim 0.2 - 0.3$ mag too blue. A similar offset is also the case for all older SSP models. The only indication of intermediate ages is the presence of half a dozen GCs with $\sim (g - k) \sim 3.7$ mag in NGC 4406. The data for the NGC 4382 and NGC 4473 GC systems should be taken with caution as they were observed in nonphotometric conditions. The data spread along $(g - k)$ is attributed to observational uncertainties or is intrinsic to the systems. For M87, the GCs present a standard deviation of ± 0.75 mag along $(g-k)$ from the best-fit line to $(g-k)$ and $(g-z)$ and the observational errors reach a maximum of ± 0.4 mag (based on Artificial-star tests). One might think that $[\alpha/\mathrm{Fe}]$ ratios could perhaps account for part of this spread, but this of course would only explain the scatter if the ratios varied among clusters. Stochastic effects in the integrated colours are investigated following Santos & Frogel (1997). It is found that the fluctuations in the number of bright stars can account for only ~ 0.1 mag of the spread in $(g - k)$ for a 14 Gyr-old SSP and a ~ 0.2 mag for a 2 Gyr one, assuming that all clusters have 10^6 stars. We conclude that age dating GC systems as old ($\sim 11, 14$ Gyr) or of intermediate age ($\sim 2, 3$ Gyr) depends on the choice of the SSP model. Padova SSPs with Marigo *et al.* (2008) isochrones for old ages are in good agreement with the data. Moreover, there is no evidence for significant differences in the GC age distributions among the galaxies studied here. NGC 4406 could be an exception.

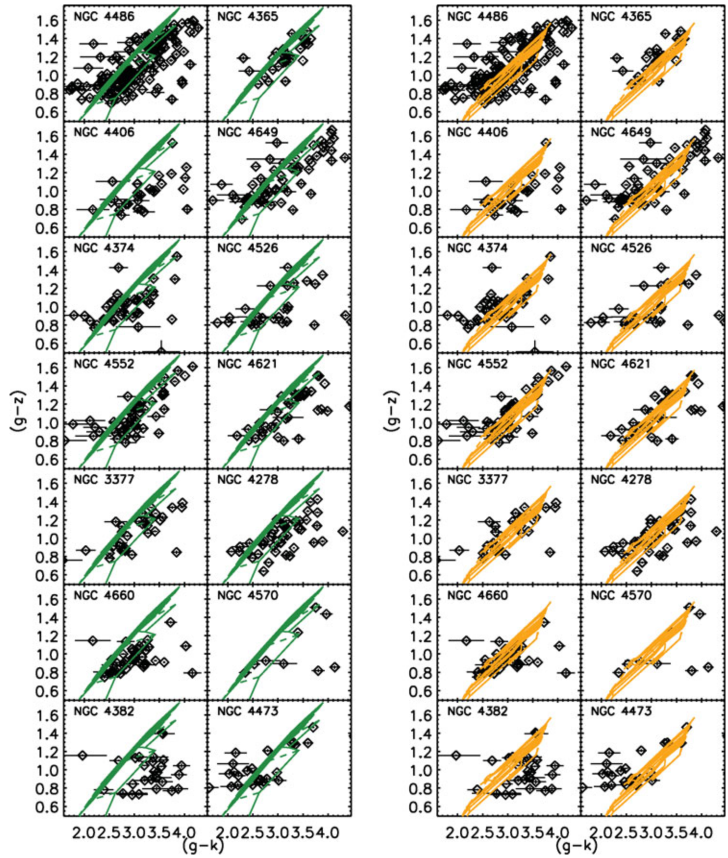

Figure 1. Two-colour diagrams for the GC systems of the 14 galaxies: $(g-k)$ versus $(g-z)$. *(left)* A model grid from Maraston (2005) is overplotted, with model sequences of constant age as solid lines: 2, 3, 4, 5, 6, 8, 11 and 14 Gyr. *(right)* A model grid of Padova SSPs with Marigo et al. (2008) isochrones is now overplotted with the same ages as in the left panel.

3. Bimodality

The combination of optical and NIR colours is a better indicator of the true underlying metallicity distribution than optical colours alone (Cantiello & Blakeslee 2007). At redder wavelengths, the stellar population will include decreasing contributions from horizontal-branch stars. If the metallicity distribution of a GC system is genuinely bimodal, this (as seen through optical colours) should be maintained as one moves to redder wavelengths. We thus test the alternative Yoon *et al.* (2006) scenario for colour bimodality.

In Figure 2. the $(g-z)$, $(g-k)$ and $(z-k)$ colour distributions for the GC systems of the 14 E/S0s shown in Figure 1. are plotted in the first, second and third panels, respectively. Note that the bimodality becomes less evident in $(g-k)$ compared to $(g-z)$ and even less pronounced in $(z-k)$. This is the colour that should have the smallest contribution from horizontal-branch stars. It is evident from this figure that the galaxies that have more than one peak in $(g-z)$ appear more strongly single peaked in $(z-k)$, while

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the multiple peaks in the $(g-k)$ distributions still appear more clearly. Note how this effect is pronounced in NGC 4486 (M 87) the most cluster-rich galaxy in the sample. This result fits very nicely into the Yoon *et al.* (2006) picture where the horizontal-branch morphology would induce a nonlinear behaviour in the colour–metallicity relation, and this would drive a unimodal metallicity distribution into a bimodal (optical) colour distribution. If in the reddest of the available colours, $(z-k)$, the best metallicity indicator available here, the distribution is unimodal, it seems straightforward to conclude that horizontal-branch morphology could be causing this. Taking into account that $(z-k)$ is the most sensitive colour among the ones available in this study to uncertainties in the K band, we tested whether this observational scatter could blur the bimodality. We carried out a linear transformation of the $(g-z)$ colour distribution to $(g-k)$ and $(z-k)$ that preserved bimodality in the absence of noise. We then simulated blue- and red-peaked Gaussian distributions, adding noise proportional to more realistic errors than the ones estimated by PHOT (calculated based on Artificial-star tests). From the results of these simulations it was found by running KMM tests that it is very likely to have a bimodal distribution, appearing more and more unimodal in the transition from the bluest $(g-z)$ to the reddest $(z-k)$ colours. Whether the absence of horizontal-branch stars in $(z-k)$ can indeed be responsible for the weakening of bimodality in this colour as opposed to $(g-z)$ (and $(g-k)$) and supports the scenario proposed by Yoon *et al.* (2006) cannot be concluded with the current data set, as observational uncertainties in the K band can also be the mechanism behind this.

3.1. *Horizontal-branch morphology*

In Figure 3, two-colour plots, $(g-k)$ versus $(z-k)$, for GCs of M87 and NGC 4649 (indicated by different symbols) are shown. Note the wavy feature the data presents around $(g-k) \sim 3.2$ and $(z-k) \sim 2$ mag. For the sake of clarity, in the left panel we show the data points alone with their corresponding error bars. A SPoT–Teramo 14 Gyr SSP with a realistic treatment of horizontal-branch morphology (Raimondo *et al.* 2005) is overplotted in the middle panel and a Padova 14 Gyr SSP with Marigo *et al.* (2008) isochrones is overplotted on the right. This wavy feature is also present in the SPoT–Teramo SSP model but does not fit well with the data, especially for the redder part. Other SSP models (Charlot & Bruzual, in prep., Maraston 2005 and Padova) that do not take into account horizontal-branch morphology do not show this behaviour, as can be seen in the right panel for the case of Padova. By comparing Figure 3 to figure 1 of Yoon *et al.* (2006), one concludes that $(z-k)$ is indeed a good indicator for [Fe/H] and that $(g-k)$ still contains some contribution of horizontal-branch stars. Higher signal-to-noise ratio, deeper data, sampling more GCs would be necessary to understand whether the nonlinear behaviour in the colour–metallicity relation induced by horizontal-branch morphology, as attested by Figure 3. would indeed drive a unimodal metallicity distribution into a bimodal (optical) colour distribution, as proposed by Yoon *et al.* (2006).

4. Conclusions

A sample of GC systems in E/S0s was observed in the K band with *WHT*/LIRIS and combined with archival *HST*/ACS imaging in the g and z bands. Based on these observations, we intended to study the overall ages and metallicity distributions of GC systems. We find that age dating GCs as old or intermediate age depends on the choice of the model. Padova SSPs for old ages ($\sim 12, 14$ Gyr) with Marigo *et al.* (2008) isochrones with a new treatment for the TP–AGB phase fit the data well. Maraston (2005) and

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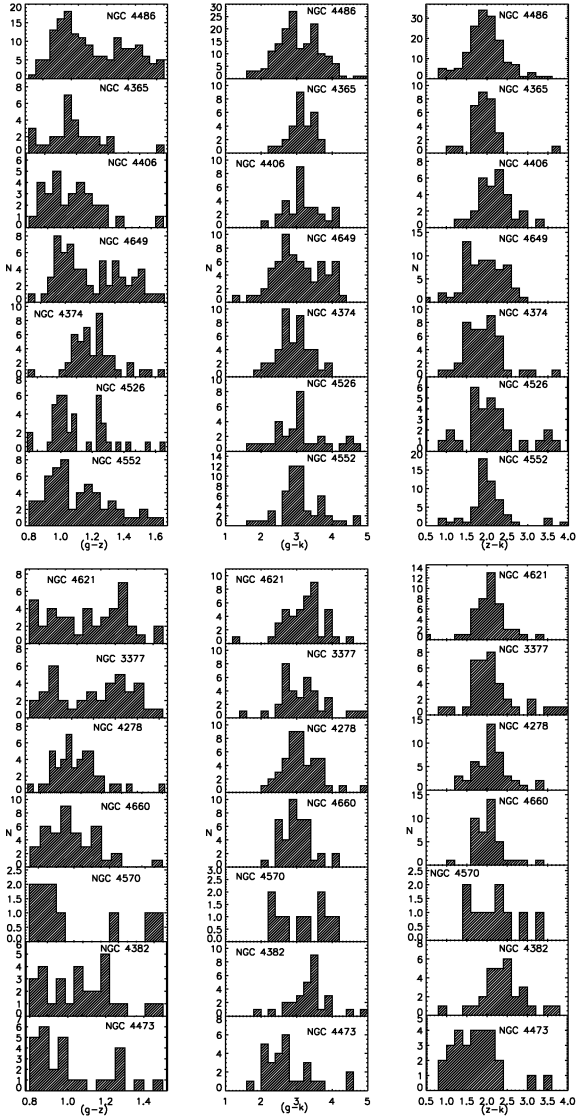

Figure 2. $(g-z)$, $(g-k)$ and $(z-k)$ colour distributions for the GC systems of the 14 E/S0s shown in Figure 1. Note that the bimodality becomes less evident in $(g-k)$ compared to $(g-z)$ and even less pronounced in $(z-k)$. The latter is the colour that should have the smallest contribution from horizontal-branch stars.

Charlot & Bruzual (in prep.) models yield intermediate ages ($\sim 2-3$ Gyr) for the majority of the GCs. The NGC 4365 GC system is not found to be an exception. In general, all GC systems in the two-colour diagrams look very much alike. NGC 4406 is found to be the strongest candidate for having intermediate ages.

As far as metallicity distributions are concerned, the bimodality becomes less evident in $(g-k)$ compared to $(g-z)$ and even less pronounced in $(z-k)$. The latter colour is the one that should have the smallest contribution from horizontal-branch stars. The disappearance of bimodality in this colour, while evident in the optical $(g-z)$ colour, could be attributed to the Yoon *et al.* (2006) effect, although the observational uncertainties could also account for it. The relation $(g-k)$ versus $(z-k)$ shows a wiggle around $(g-k) \sim 3.2$

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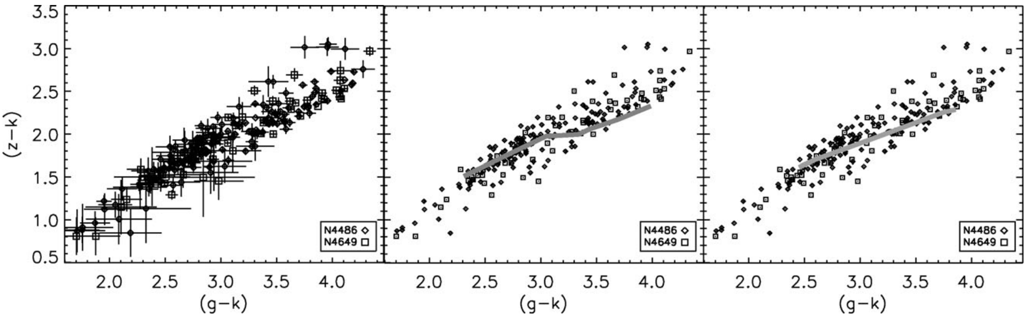

Figure 3. Two-colour plots, $(g-k)$ versus $(z-k)$, for GCs of M87 and NGC 4649, indicated by different symbols. The error bars are only presented in the left panel, for clarity. Note the wavy feature the data present around $(g-k) \sim 3.2$ and $(z-k) \sim 2$ mag. The SPoT–Teramo 14 Gyr SSP with a realistic treatment of horizontal-branch morphology (Raimondo *et al.* 2005) is overplotted in the middle panel and the Padova 14 Gyr SSP with Marigo *et al.* (2008) isochrones is overplotted in the right panel.

and $(z-k) \sim 2$ mag, which is present in the 14 Gyr SPoT–Teramo SSP models, which include a proper treatment of horizontal-branch morphology. It is concluded that redder colours, such as $(z-k)$, are ideal metallicity indicators.

This study calls attention to the importance of choice of SSP models. How well a set of models fits the data seems to be linked to which stellar evolutionary stages are incorporated in it and how this is done. As far as deriving overall ages of GCs with the optical/NIR imaging technique, it becomes clear that different kinds of TP–AGB treatments yield different results. SSPs including recent TP–AGB models are consistent with old GC ages. The addition (or not) of a realistic treatment of the horizontal-branch morphology can also make a big difference. Whether or not this evolutionary phase is responsible for optical colour bimodality cannot be answered with the data here presented.

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