On Synchronized Globular Cluster Formation over Supra-galactic Scales: A Virgo-Centaurus Group Connection

Juan C. Forte,1,2⋆

1 Academia Nacional de Ciencias de Buenos Aires, Av. Alvear 1711, 1014, Buenos Aires, Argentina
2 Academia Nacional de Ciencias, Av. Velez Sarsfield 249, X5000JJC, Córdoba, Argentina

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

This work reports the detection of a multi-peaked colour pattern in the integrated colours distribution of globular clusters associated to the giant elliptical galaxy NGC 4486, using Next Generation Virgo Survey data. This feature is imprinted on the well known bimodal colour distribution of these clusters. Remarkably, the pattern is similar to that found in previous works, based on photometry from the HST − Advanced Camera Virgo Survey, in less massive Virgo galaxies. This characteristic can be traced up to to 45′ (≈217 Kpc) in galactocentric radius. This suggests that globular cluster formation in Virgo has been regulated, at least partially, by a collective process composed by several discrete events, working on spatial scales comparable to the size of the galaxy cluster. Furthermore, the presence of a similar colour pattern in NGC 5128, at the outskirts of the Virgo Super − cluster, poses an intriguing question about the spatial scale of the phenomenon. The nature of the process that leads to the colour pattern is unknown. However, energetic events connected with galaxy or sub-galaxy cluster mergers and SMBH activity, in the early Universe, appear as possible candidates to explain an eventual enhancement/quenching of the globular clusters formation, reflected in the modulation of their integrated colours. Such events, presumably, may also have had an impact on the whole star formation history in Virgo galaxies.

Key words: galaxies: star clusters: general

1 INTRODUCTION

An increasing volume of observations in the high redshift domain (see, for example, Izumi et al. 2021), as well as inferences from cosmological models, converge to show that the early Universe was dominated by complex and energetic interactions that had an impact on the post temporal evolution of galaxies.

In turn, and for a long time, globular clusters (GCs) have been known as old systems and recent estimates place the origins of the oldest ones within a couple of hundred Myr after the Big Bang (e.g. Valcin et al. 2020). In this context, some GCs that are observable in the the local Universe, appear as potential candidates to search for eventual information about those early events.

For the last twenty five years, a dominant paradigm in extra galactic GCs research, has been the so called "bimodality". This term indicates that most GCs belong to one of two families. On one side, blue clusters with low metallicity and shallow spatial distributions and, on the other, red clusters with higher metallicities and more concentrated towards the galaxy centres.

Written several years ago, the dawn of this concept has been thoroughly described in Brodie & Strader (2006). A connected, and even earlier precedent, can be found in Forte et al. (1982) who explained previous results by Strom et al. (1981) in NGC 4486 on the basis of "original" (associated to the galaxy halo) and "external" (accreted from Virgo dwarf galaxies) GCs.

Integrated colours of old stellar systems are a proxy to metallicity and the GCs colour distributions (GCCDs) give an idea about the chemical content of each of the cluster sub-populations. Bimodality seems to have a direct connection with the halo-bulge structure observed in the MW and in other galaxies. A key contribution to this subject, based on HST − ACSVS observations of GCs in the Virgo cluster, has been presented by Peng et al. (2006).

The interest in the study of GCCDs in different galaxies had a strong motivation in the frame of the Ashman & Zepf (1992) scenario. These authors suggested that merger events may have triggered the formation of massive stellar clusters (eventually, GC progenitors) then leaving distinct imprints on the GCCDs. However, the attention of following papers has been more concentrated on the bimodality issue than on the eventual presence of subtle features. Deviations from bimodality are usually explained as the result of the sampling noise associated with stochastic processes.

A summary about the status of bimodality in the context of...
extragalactic GCs research was presented some years ago in Harris et al. (2017), who also emphasized the need to advance beyond that concept.

An exploratory attempt in that direction was introduced in Forte (2017) (F2017 in what follows). The idea behind that work is that, even though the GCCDs in different galaxies should reflect their individual formation process, the presence of common features might be detectable on large composite scales. This approach was tested on the HST – ACSV S photometric data published by Jordán et al. (2009) and Jordán et al. (2015) for GC systems in the Virgo and Fornax clusters, respectively (see Section 2).

The presence of multi-peaked colour patterns was detected on composite GC samples associated with non-giant, moderately bright galaxies (i.e., $M_g$ from -20.2 to -19.2), in both galaxy clusters. These features were dubbed as the template Virgo and template Fornax patterns (TVP and TFP, respectively).

A comparison of the GC colour patterns in these galaxy clusters shows some similarities and differences. For example, the Virgo GCs exhibit two blue components, with peaks at $(g-z) = 0.85$ and 0.95, while the Fornax pattern has a single broad blue peak at $(g-z)=0.94$. Other five, redder colour peaks in Fornax, are some 0.03 mag bluer than their Virgo counterparts.

A subsequent paper, Forte et al. (2019), extended the analysis to the central regions of giant galaxies in Virgo and confirmed the presence of TVP-like colour structures in the inner regions of these systems.

Photometric errors, field contamination, and statistical noise, were analysed and rejected as possible spurious origins of these patterns.

The physical origin of the template patterns is not known and further efforts in clarifying their nature might not be justified without a tentative scenario. A (cautious) working hypothesis, presented in F2017, assumes that colour peaks in the GCCDs are set during periods of star-burst activity, including an enhancement of GC formation, within a total temporal span of $\pm$1.5 Gyr in the time scale defined by the SSP models presented by Bressan et al. (2012).

If the colour patterns arise as the result of different external events, a chronological scale could be defined since chemical abundance $[Z/H]$ correlates with time. In fact the GCCD may reflect either a temporal sequence (where $[Z/H]$ is a clock), a positional sampling (halo; bulge), or eventually, a combination of both. This seems to be the case of GCs in the MW (Leaman et al. 2013; Massari, D. et al. 2019), that exhibits a bifurcated age-metallicity relation (i.e. halo/blue or bulge/red GCs).

If comparable relations hold in other galaxies, different events may have left simultaneous imprints (colour peaks) on both the blue and red GC populations, as their respective metallicities increased simultaneously with time (see Fig. 30 in F2017). The hypothesis requires external stimuli, working on large spatial scales, and able to unleash simultaneous GC formation on all cluster galaxies. It is worth mentioning that, evidence in favor of GC formation synchronicity, in the case of the MW and the LMC, has been presented by Wagner-Kaiser et al. (2017).

Some results that deserve further attention in connection with the tentative landscape described above are:

(i) The existence of intense star-formation widespread on a spatial scale of several Mpc can be seen in the low redshift ($z=0.19$) "Sausage cluster" (CIZAJ2248 + 5301). In this merger of galaxy clusters Stroe et al. (2015), and Sobral et al. (2015), find a gravitational shock wave, fuelled by the merger, that has triggered a viral star forming process within a short time interval.

(ii) Forrest et al. (2020) analyse the characteristics of galaxies with a range of redshift $z$ from 3 to 6 and conclude that their star formation histories are compatible with the presence of several, intense and short-lived, star formation events, followed by quenching periods. This is consistent, for example, with a previous analysis by Schulz et al. (2015) in their study of the stellar populations in NGC 1399, one of the central galaxies in the Fornax cluster.

(iii) Martin-Navarro et al. (2021) find evidence of the impact of super massive black holes (SMBHs) on modulating the star formation rates in satellite galaxies. The main argument behind their results is that quiescent satellite galaxies are less frequent in the direction of the minor axis of their central galaxies. This is interpreted as a consequence of the effect of the SMBHs activity on the circumgalactic medium and the star formation rates.

All these results may provide a starting frame to clarify which physical mechanism, or eventually a combination of them, could be responsible for the observed template patterns. For example, merger induced star bursts, followed by a period of quenching originated by SMBH feedback, looks as a possible scenario for further exploration.

This work is focused on the abundant GC population of the giant elliptical NGC 4486, one of the central galaxies in the Virgo cluster, in an effort to detect the eventual presence of a colour pattern comparable to that seen in the non-giant galaxies in the same cluster. The detection of a TVP-like structure in the inner region of NGC 4486 ($R_{gal} =0.6'$ to 1.5') has been already noted in Forte et al. (2019) (see their Fig. 7) using ACSV S data (Jordán et al. 2009). The eventual detection of such a pattern on a large angular field, and on a different data set, would provide a strong support in favor of a physical nature of the observed GCs colour modulation.

For the following discussion we adopted the photometric catalogue presented by Oldham & Auger (2016) (OA2016 in what follows), based on ugriz NGVS data (Ferrarese et al. 2012). Those authors performed a census of the NGC 4486 GC populations, based on a Bayesian approach. Their model, aimed at describing the overall properties of the GC system, includes twenty three parameters, and assigns to each object a given probability of being a GC or a field object, based on its image shape, brightness, colour and spatial position.

As an alternative, and complementary procedure, the present work separates GCs and field contaminants through fits of ugriz pseudo-continuums to the photometric data of each object (Forte et al. 2013), as explained in the Appendix.

This work also introduces a random sub-sampling (RSS) approach, similar to that used in Bootstrapping analysis, aiming at identifying colour structures in the GCCDs, that can be compared with those found in F2017.

In this approach, sub-samples of a larger GC population, are randomly and repetitively chosen. Colour peaks on each
sub-sample are identified on their smoothed GCCDs (at the colours with null derivatives) and catalogued.

We note that the RSS analysis allows for the detection of colour peaks possibly hidden in colour intervals where the GCCDs exhibit high slopes (e.g., the blue and red wings of the dominant blue GC’s sub-population).

The structure of the paper is as follows: Section 2 presents a review of the Virgo pattern, introducing a RSS analysis of composite GC samples. Section 3 deals with the homogenization of the colour-colour relations relevant to this work (as detailed in the Appendix). The results from the analysis of the ugriz photometric data are given in Section 4. The characteristics of the colour pattern found in the field of NGC 4486 are discussed in Section 5. The case of GCs associated to NGC 5128, at the edge of the VirgoSuper − cluster, is presented in Section 6. Finally, a summary of the results and the conclusions are presented in Sections 7 and 8, respectively.

2 REVIEWING THE TEMPLATE VIRGO PATTERN

The results presented in F2017 were based on the analysis of (g − z) colours (ACSVS system) from Jordán et al. (2009). Composite GC samples, within a galactocentric radius (Rgal) of 110″, were taken from different galaxy groups contained in a moving sampling window, defined in the absolute magnitude \( M_g \) vs. \((g − z)\) colour plane.

Each of those GC colour samples was smoothed with a Gaussian kernel (see below) and colour peaks were identified. The statistics of these colours, in turn, define the relative frequency of appearance of each of these peaks in different samples. In what follows, these components are identified with their \((g − z)\) colours (either in the ACSVs or SDSS photometric systems) given within brackets.

The size of the smoothing kernel requires a proper tuning, since a wide kernel will erase eventual colour features while a narrow one, will lead to oversampling, and spurious colour peaks.

In order to have a quantitative estimate of the proper kernel size, we used Monte − Carlo models. These models include Gaussian integrated luminosity functions and different GC colour distributions with bimodal or multi peaked patterns.

Simulated photometric errors were added (using the \( \text{rms} \) values presented in different photometric works) before proceeding to the smoothing and colour pattern analysis. For each model GC, the photometric errors were assigned adopting those of the nearest observed cluster neighbour in a \( g \) vs. \((g − z)\) magnitude-colour diagram.

In the case of the ACSVs \((g − z)\) data from Jordán et al. (2009), stable features are detected with a 0.035 mag \( \text{FWHM} \) Gaussian kernel (i.e \( \sigma_{(g−z)} = 0.015 \) mag).

Throughout this paper, kernel sizes are given in terms of \( \text{FWHMs} \).

Numerical models are also useful to estimate the probability of generating a TVP-like GCCD, just as a result of sampling noise on a bimodal GCCD characterized by two (blue and red) Gaussian colour distributions, and photometric errors comparable to those given by Jordán et al. (2009).

After \( 10^3 \) realizations, only five percent of the model outputs, aimed at reproducing multi-peaked GCCDs, show similarities with the TVP. This similarity is quantitatively defined by means of the \( \text{rms} \) of the colour differences between a given model colour peak and the colour of the nearest peak in the TVP.

The same models were used to estimate the effectiveness of

\[ \text{Figure 1.} \quad (g − z) \text{ colour peak frequencies derived from a RSS routine for 2235 GC’s colours in seventy one Virgo non-giant galaxies. The histogram has 0.02 mag bins, while the blue line corresponds to a Gaussian smoothing kernel with 0.023 mag FWHM. The open dot at } (g − z) = 1.35 \text{ indicates a peak not detected in a previous analysis (see text). Dashed lines correspond to the revised TVP colours.} \]

\[ \text{Figure 2.} \quad (g − z) \text{ colour distribution corresponding to a composite sample of 511 clusters in six galaxies with } M_g \text{ from -20.2 to -19.7. The blue line is the (arbitrarily) scaled down frequency curve shown in Fig. 1. The peak at } (g − z) \approx 1.35 \text{ only appears for clusters in NGC 4442. Dashed lines correspond to the TVP colours.} \]
Figure 3. $(g - z)$ colour distribution corresponding to a composite sample of 543 clusters in seven galaxies with $M_g$ from -19.7 to -19.2. The blue line is the (arbitrarily) scaled down frequency curve shown in Fig. 1. Dashed lines correspond to the TVP colours.

Figure 4. $(g - z)$ colour distribution corresponding to a composite sample of 1181 clusters in fifty eight Virgo galaxies with $M_g$ from -19.2 to -16.0. The blue line is the (arbitrarily) scaled down frequency curve shown in Fig. 1. Dashed lines correspond to the TVP colours.

The RSS approach in assessing the presence of colour peaks in a given GCCD. The results indicate that for a population in the order of $10^3$ GC candidates, a sub-sampling size of about ten percent of the total, leads to the recovery of the input patterns after a few hundred sampling cycles.

It must be stressed that the RSS technique, “per se”, is not able to discriminate between a pattern with a physical entity or, eventually, one arising in statistical fluctuations connected with stochastic processes. However, these last type of fluctuations are fragile to sub-sampling, in contrast with the characteristics of the TVP features, that survive to different sampling criteria as discussed in F2017.

Fig. 1 shows the RSS output corresponding to 2235 GCs in seventy one Virgo galaxies with $M_g$ between -20.2 and -16.0, adopting a sub-sampling size of 10 percent, and $5 \times 10^2$ random sampling cycles, that produced 5344 colour peaks. For this sample we set a limiting magnitude $g = 24.0$ (similar to that in the OA2016 work). The $(g - z)$ colour peak statistics is given in the form of a discrete histogram (bin size: 0.02 mag) and also after smoothing with a narrow 0.023 mag Gaussian kernel.

Dashed lines in Fig. 1 correspond to the revised TVP colours adopted in what follows, namely, $(g - z)_{ACSVS}$: 0.72; 0.85; 0.93; 1.03; 1.13; 1.21; 1.29; 1.39; 1.47; and 1.60. These colours are independent of galaxy sampling windows, and are preferred to those presented in F2017, shown as black dots in the upper part of the diagram.

A comparison between the revised TVP colours and those of the previous determination, shows small differences with maximum deviations of $\approx 0.02$ mag. The open dot in Fig. 1 identifies a peak at $(g - z) = 1.35$, not detected in F2017. This peak mostly appears in GC candidates with galactocentric radii between 30′′ and 60′′ associated to NGC 4442 (VCC 1062).

The [1.72] peak, reported in F2017 and not present in this figure, is the result of field contamination (as seen in the following Fig. 5 and Fig. 6). However, a peak at [1.69] seems present in the inner regions of NGC 4486 (see Section 5).

The GCCD for all the clusters in the sample are displayed in Fig. 2, Fig. 3 and Fig. 4. These distributions, and similar ones throughout the paper, are normalized by the total number of objects in each sample.

The first two diagrams include half of the total GC sample associated to the brightest 13 galaxies (1054 objects), split in two sub-samples (in six and seven galaxies) with approximately the same number of objects. Black dots correspond to the colour peaks found on the GCCD after smoothing with a 0.035 mag Gaussian Kernel. The main features of the TVP colours are common to both diagrams.

In turn, Fig. 4 includes 1181 GC candidates in 58 galaxies with $M_g$ in the range from -19.2 to -16.0. This sample, shows a dominant blue peak [at $(g - z) = 0.87$], in contrast with the double peak ([0.85];[0.93]) detectable in the brighter galaxies.

3 REFERENCE COLOURS FRAME AND GLOBULAR CLUSTER CANDIDATES FROM PHOTOMETRIC DATA

A problem for the comparison of the GCCDs in different galaxies arises in the various photometric systems, photometric zero points, interstellar reddening corrections, and also in the criteria to define GC candidates, adopted in different works. These differences may conspire against the identification of eventual common features.

This work adopts the SDSS $ugriz$ multicolour relations defined by Virgo galaxies brighter than $g = 14.0$ as presented by Chen et al. (2010). The rationale behind adopting the
integrated colours of early Virgo galaxies as a reference frame, is that these systems are composed by a number of GCs−like old stellar sub-populations. The similarity between the slopes of the colour-colour relations of GCs and galaxies was noted, for example, in Forte et al. (2014).

The definition of the forty five colour-colour relations that can be obtained from ugriz magnitudes, the transformation of magnitudes from the NGVS to the SDSS system, and the identification of GC candidates through pseudo-continuum fits, are described in the Appendix. In particular, the relation between the \((g − z)\) colours in both photometric systems results:

\[
(g − z)_{SDSS} = 1.090(g − z)_{NGVS} + 0.05
\]

with uncertainties of ±0.02 and ±0.015 for the slope and zero point terms, respectively.

4 GLOBULAR CLUSTER CANDIDATES IN NGC 4486 FROM NGVS DATA

The present work is restricted to an area with a galactocentric radius \(R_{gal}\) range from 0.5′ to 60′, i.e., not including the innermost core of NGC 4486, where the completeness of the OA2016 work is affected by the galaxy halo brightness. The studied region has a total areal coverage of 85 percent and avoids the "Markarian’s Chain" galaxies, located towards the NW of NGC 4486.

In what follows, and from the Schlafly & Finkbeiner (2011) maps, we adopt a mean colour excess \(E_{B−V} = 0.024\) and then, interstellar extinction values of 0.123; 0.087; 0.065; 0.051 and 0.034 mag, for the \(u, g, r, i, z\) bands, respectively.

The results based on NGVS data presented by Muñoz et al. (2014) and Powalka et al. (2016), show the complexity of disentangling GC populations from field objects based purely on photometric data. These results also indicate that, using single colour photometry and adopting "reasonable" colour ranges to identify GCs, will not avoid a significant fraction of field contaminants. The presence of these field objects, in turn, could mask the eventual detection of subtle colour patterns.

As an attempt to identify GC candidates in this region, we assume that the empirical relations given in the Appendix, define the locus of GCs in a multi-colour space. In this approach the status of GC−candidate is earned if the residuals left by the fits of the ugriz pseudo-continuums, listed in Table A2, fall within the acceptability boundaries defined by the \(α = 0.35 \pm 0.05\), and \(a = 0.03 \pm 0.005\) parameters (see the Appendix), and have a probability \(P > 0.5\) of being either a genuine blue or red cluster according to OA2016.

The \((g − i)\) vs. \((g − z)\) and \((u − z)\) vs. \((g − z)\) diagrams for all the 13271 objects brighter than \(g = 24.0\), within \(R_{gal} = 60′\) are presented in Fig. 5 and Fig. 6. In turn, the same diagrams for 6306 objects considered as GC candidates are displayed in Fig. 7 and Fig. 8, respectively.

The integrated GCs luminosity function for all the GC candidates within \(R_{gal} = 60′\) is displayed in Fig. 9. This radius corresponds to 290 Kpc, adopting a distance modulus \(V − M_V = 31.1\), derived by Tonry et al. (2001).

As a reference, Fig. 9 includes a Gaussian function characterized by a turn over magnitude \(g = 24.0\) and a dispersion \(σ_g = 1.35\) mag. These parameters are representative for GCs associated with giant galaxies in Virgo (e.g. Villegas et al. 2010).

The \(g\) magnitude distribution for objects considered as field interlopers (MW stars and unresolved extragalactic objects), discussed in detail in OA2016, is shown as dashed lines.

The projected position of the GC candidates on the sky is seen in Fig. 10. This diagram combines the position of these globulars with an smoothed image (adopting a 1.75′ bi-
Figure 7. \((g-i)\) vs. \((g-z)\) colours diagram for 6306 objects considered as GC candidates within 60′ from the centre of NGC 4486. The red line indicates the colour-colour relation for globular clusters derived from Table A2.

Figure 8. \((u-z)\) vs. \((g-z)\) colours diagram for 6306 objects considered as GC candidates within 60′ from the centre of NGC 4486. The red line indicates the relation for globular clusters derived from Table A2.

Figure 9. Integrated GCs luminosity function for 6306 GC candidates within \(R_{gal} = 60′\) in NGC 4486. The solid curve is a reference Gaussian with \(\sigma_g = 1.35\) mag. and a turn-over at \(g = 24.0\). The dashed histogram corresponds to 6817 objects considered as field interlopers.

In Fig. 10 are labeled as a, b, c, and d. In particular, the feature identified as a has been discussed by Romanowsky et al. (2012), using radial velocity data presented in Strader et al. (2011) (ST2011 in what follows). Their analysis indicates that in fact, this feature is a tidal stream delineated by GCs over a range of \(\approx 35′\).

The \((g-z)\) vs \(R_{gal}\) values for GC candidates within \(R_{gal} = 60′\), is displayed in Fig. 11. This figure also includes 1170 objects (green dots) that fall inside the photometric acceptability boundaries, but have \(P < 0.50\) and were considered as field interlopers. These objects show systematic deviations from the GC colours locus, and no concentration towards the galaxy centre.

Fig. 11 is comparable, for example, to that presented by Ko et al. (2022), using the \((g-i)_{NGVS}\) colours, on a larger galactocentric range. In a vertical reading of their Fig. 2, these authors detect a small colour gradient for red GCs and a steeper one for blue GCs. An alternative view of this kind of diagrams is given in Section 6.

A first hint about the presence of the TVP within a galactocentric radius of 60′ is provided by Fig. 12. This diagram corresponds to the \((g-z)\) GCCD of a sub-sample of 4474 GC candidates, with \(P > 0.90\) (black line). This distribution shows a prominent blue peak at \((g-z) = 0.87\), close to that observed in the composite GCs sample corresponding to galaxies fainter than \(M_g = -19.0\) (see Fig. 4), and other five redder peaks at the expected positions of the TVP components.

Fig. 12 also includes the GCCD for 1832 GC candidates with \(P\) from 0.50 to 0.90 (blue line). This sample shows barely detectable colour peaks but, again coincident with those of the TVP.

dimensional Gaussian kernel). The combined image exhibits several azimuthal inhomogeneities. The presence of spatial structures that seem the result of recent or ongoing galaxy mergers, has been noted in the extensive analysis of GCs in the Virgo cluster by Durrell et al. (2014).

Four of the most prominent radial stream-like structures
5 COLOUR PATTERN IN THE GCCD OF GLOBULAR CLUSTERS ASSOCIATED TO NGC 4486

The analysis of both the GCCDs and of the RSS outputs as a function of galactocentric radius and position angles, finds a region between $R_{\text{gal}} = 5'$ and $9'$ and P.A. from $270^\circ$ to $345^\circ$, where the colour pattern is not clearly defined. This region includes 268 objects that, both on statistical and photometric terms, can be considered as genuine GC candidates. These objects constitute $\approx 4$ percent of the total sample and were removed for the following discussion. This leaves a total of 6038 GC candidates for the analysis of the colour pattern.

The RSS routine was run on this last sample (performing $5\times10^2$ random sampling cycles), on both the O2A2016-NGVS $(g - z)$ colours, and on their transformed version to the SDSS system. The correlation of the TVP peaks found in the SDSS system, as well as those in the ACSVS system (discussed in Section 2), against the NGVS peaks, are presented in Fig. A5. This diagram indicates that there are no significant differences between the TVP $(g - z)$ colours in the ACSVS (filled dots) and in the SDSS (open dots) systems.

Fig. A5 also includes the $(g - z)$ colour relation derived in Section 3 (blue line), which is in very good agreement with that presented by Wu et al. (2022) (red line). Their relation was shifted by +0.015 mag in ordinates, indicating the existence of a small zero point difference with this work.

The TVP $(g - i)$, $(g - z)$, and $(u - z)$ colours in the SDSS system assuming, from the previous result, that the $(g - z)$ colours are coincident with those in the ACSVS system, are listed in Table A3.

The output from the RSS routine, corresponding to 6038 GC candidates within $R_{\text{gal}} = 60'$ and using the same smoothing kernel (0.035 mag) adopted in Section 2, is presented in Fig. 13. This diagram includes 4799 colour peaks, after $5\times10^2$ sampling cycles. A comparison with the TVP colours listed in Table 3 yields $\sigma_{(g-z)} = 0.016$, and a maximum deviation of +0.03 mag from that pattern, occurs for the peak at $(g - z) = 1.50$.

By contrast, none of these features are detectable in the $(g - z)$ colour distribution of 6817 objects considered as field interlopers (see Fig. A6).

Both the nature of the peak at $[1.69]$, in Fig. 1, and the meaning of the horizontal lines in Fig. 13, linking given blue and red colour peaks separated by 0.36 mag intervals, are discussed in Subsection 5.2.

5.1 Globular clusters colour pattern in the inner 5′ region of NGC 4486

The RSS analysis of GC candidates in different galactocentric regions, indicates that most of the pattern seen in Fig. 13 arises close to the centre of NGC 4486.

The $(g - z)$ GCCD for 1591 GC candidates within $R_{\text{gal}} = 5'$, displayed in Fig. 14, shows the presence of seven peaks coincident with the TVP colours ($\sigma_{(g-z)} = 0.012$ mag). The arbitrarily scaled down RSS output displayed in Fig. 13, is also included in this diagram (lower blue curve).

Restricting the analysis to $R_{\text{gal}} < 2.5'$, reveals the presence of a single blue peak (with an extended tail towards the blue) as seen in Fig. 15. A similar blue peak, and colour peak structure, is found by Bellini et al. (2015) in their HST photometric survey, including the ultraviolet filter F275W, in the same area (see Fig. 6-cl in that work).

In turn, Fig. 16 corresponds to 924 GC candidates in the $R_{\text{gal}}$ range from $2.5'$ to $5'$. This figure shows a decrease in the number of red clusters, a prominent double blue peak structure ([0.87] and [0.95]), comparable to those seen in Fig. 2 and Fig. 3, as well as other five redder colour peaks, consistent with the TVP colours ($\sigma_{(g-z)} = 0.011$ mag).
Figure 12. $(g - z)$ colour distribution for 4474 GC candidates with $P > 0.90$ (black line) and for 1832 GC candidates with $P$ from 0.50 to 0.90 (blue line), within $R_{gal} = 60'$ in NGC 4486. Dashed lines correspond to the TVP $(g - z)$ colours in the SDSS photometric system.

Figure 13. Relative frequency of $(g - z)$ colour peaks found by the RSS routine on a sample of 6038 GC candidates within $R_{gal} = 60'$ in NGC 4486. Vertical dashed lines indicate the TVP $(g - z)$ colours discussed in Section 2. Horizontal lines (linking given blue and red peaks) have a length of 0.36 mag (see Section 5).

A further scrutiny about the presence of the TVP within $R_{gal} = 5'$, can be performed using GCs with measured radial velocities and $(g - i)$ colours as presented by ST2011. In this last work, the original $(g - i)$ colours were taken from Harris (2009) and were transformed to the SDSS photometric system. The sample includes 340 GCs, as well as 39 objects with half light radii > 5 $Pc$ (classified as “extended” or UCD objects), in a $g$ magnitude range from 19.0 to 23.5 and radial velocities from 500 km s$^{-1}$ to 2500 km s$^{-1}$.

The $(g - i)$ colour distribution for these objects is displayed in Fig. 17, where dashed lines represent the TVP $(g - i)$ colours listed in Table A3. Taking into account that the sensitivity of $(g - i)$ to metallicity is about seventy percent of that of the $(g - z)$ colour, the smoothing Gaussian kernel was set to 0.026 mag.

Fig. 17 preserves most of the characteristics of the GCCD seen in Fig. 14, i.e., seven peaks consistent with the TVP colours, and an overall $\sigma_{(g-i)} = 0.017$ mag. We note that the feature at $(g - i) \approx 1.0$ [or $(g - z) = 1.22$] seems broader than the other red peaks, as also suggested by the two colour analysis presented below.

5.2 Spatial distribution of the TVP components and GC colour gradients

The determination of the GC areal density profiles is usually performed in terms of $R^{1/4}$, power laws, or of Sérsic profiles (Sérsic 1968).

However, a first approach to analyse the spatial distributions of each TVP components, avoiding the election of a given dependence, can be performed by determining their median galactocentric radius ($R_{med}$), and the radius that contains 90 percent of the total population ($R_{90}$). This is
a horizontal reading of the data as an alternative to the vertical reading in Ko et al. (2022) (see their Fig. 2).

In order to isolate the GCs associated with a given TVP component, we adopted a $3-D$ colour space defined in terms of the $(g-i)$, $(g-z)$, and $(u-z)$ colour indices. This last colour index is the most affected by photometric errors but it is a good discriminant between genuine GCs and field objects (see Fig. 6 and Fig. 8).

The mean separation of the TVP components in the $(g-z)$ colour is $\approx 0.09$ mag and, taking into account the slopes of the relations between these three colours, this separation becomes $0.22$ mag in the $3-D$ colour space. Then, we used volumetric sampling radii of $0.11$ mag (i.e., the $3-D$ peak-to-valley separation), centered on each of the eleven TVP colours listed in Table A3.

The distribution of the $(u-z)$ colours of 4008 GC candidates contained in these eleven volumetric samples, as a function of galactocentric radius, is presented in Fig. 18, where horizontal lines indicate the position of the $(u-z)$ TVP peaks listed in Table A3. The pattern component at $(u-z)=3.76$ (or $[1.69]$) corresponds to the reddest feature seen in Fig. 13.

Fig. 18 shows a continuous increase of both $R_{\text{med}}$ and $R_{\text{90}}$ as the GC colours become bluer, for all the TVP components. In the case of red GCs, the $R_{\text{med}}$ parameter increases from $1.25^\prime$ to $7.25^\prime$, and from $7.25^\prime$ to $40^\prime$ for the blue GCs.

A "glitch" in these trends, for both characteristic radii, is detected at $(u-z) \approx 2.50$, that corresponds to $(g-z) \approx 1.15$.

This feature is persistent to different sampling criteria (e.g., to changes in the limiting magnitude, or position angle ranges).

The variation of the $R_{\text{med}}$ and $R_{\text{90}}$ radii with integrated colours, that can also be seen for GC candidates in the colour "valleys", imply that the customary approach of characterizing blue and red GCs by means of two different areal density profiles, is only a first approximation to a more complex situation.

In their kinematic study of planetary nebulae and GCs in NGC 44486, Doherty et al. (2009) derive an outer limit for the stellar halo at $R_{\text{gal}} \approx 35^\prime$. In turn, Durrell et al. (2014) find that red GCs, disappear at $R_{\text{gal}} =45^\prime$. These results are consistent with Fig. 18. The two bluest TVP, components ($[0.72]$ and $[0.85]$), in fact reach the outer galactocentric limit of this work at $R_{\text{gal}} =60^\prime$, as also seen in the areal density profile for blue GCs presented by those last authors.

The smoothed version of the $(g-i)$ vs. $(g-z)$ colours relation for 5647 GC candidates within $R_{\text{gal}} =45^\prime$ is displayed in Fig. 19. This diagram was obtained by mapping those colours on a $501 \times 501$ matrix, that was transformed to a fits image, and smoothed with a bi-dimensional Gaussian $0.035$ mag kernel, through the irafil and gaus routines in IRAF. In this diagram the GC population with $(g-z) < 1.09$ has been scaled down by a factor $0.35$ in order to decrease the ratio of blue to red clusters and to allow the simultaneous display of all the detected colour peaks.

This last figure shows two dominant blue peaks, and other six redder features, identified by the $(g-z)$ colours of their maximum values and relative heights (normalized to the peak value at $(g-z)=0.86$). A comparison of these eight features with the TVP colours yields $\sigma_{(g-z)} = 0.018$. In particular, the $[1.05]$ peak is not seen, as it is located on the steep red wing of the $[0.94]$ peak (although that peak is present in Fig. 1, Fig. 2, Fig. 3, Fig. 13 and Fig. 17).

The detectability of the TVP over a $R_{\text{gal}}$ range of $45^\prime$, suggests null or very small galactocentric colour gradients for each of the individual pattern components (but see Section 7). This conclusion is also supported by Fig. A7 that corresponds to the smoothed GCCD (Gaussian kernel: $0.035$ mag).
of three equal number samples ($\approx$1350 GC candidates each, with $P > 0.90$ and $R_{gal}$ ranges from 0.5' to 5', 5' to 14' and 14' to 45'.

Fig. A7 shows that the colour peaks appear approximately at the same positions (with differences of, at most, 0.03 mag), regardless of the galactocentric range of the sample. The red lines and dots correspond to the innermost sample and exhibits the reddest detected peak at $(g - z) = 1.50$. This peak dissappears in the intermediate sample (black lines and dots), while the red TVP features become less evident in the outer sample (blue lines and dots).

Regarding the individual components of the TVP, we note that:

(i) The nature of the bluest peak ([0.72]) is not clear, as GC candidates do not show a definite concentration towards the centre of the galaxy. An open question connected with these objects is if, at least a fraction of them, might belong to a family of intra-cluster GCs (Ko et al. 2017).

(ii) The [0.85] peak is barely present in the central region of the galaxy but becomes detectable for $R_{gal} > 2.5'$. 

(iii) The bluest peaks, at [0.72] and [0.85], reach and exceed, the outer galactocentric boundary in this work.

(iv) The [1.03] peak is the less evident blue feature in the TVP. Its detectability is difficult in the GCCDs, as it lies on the red side of the prominent [0.93] blue peak. However, its presence is seen in two different RSS outputs (see Fig. 1 and Fig. 13), and also in the GC sub-sample with radial velocities, at $(g - i) = 0.86$ (see Fig. 17).

(v) The colour features at [1.21], [1.29], [1.39] and [1.47] appear as the most evident red peaks. In particular, the [1.21] peak seems a somewhat broad feature as seen both in Fig. 17 and in Fig. 19.

(vi) The reddest peak ([1.72]) found in F2017, appears in a region where the TVP definition is not clear and a certain degree of field contamination would be expected (see Fig. 5 and Fig. 6). However, the ugriz fits identify GC candidates clearly concentrated inside $R_{gal} = 3'$, producing a peak at [1.69], and suggesting that they are genuine clusters.

(vii) Excluding the [0.72] peak that, as noted, has a dubious nature in terms of its connection to the galaxy, the $(g - z)$ colour separations between the remaining ten TVP components range from 0.08 to 0.13 mag in $(g - z)$.

The "best" association between blue and red colour peaks,
in terms of uniform colour separations, occurs for the [0.85]-[1.21], [0.93]-[1.29], [1.03]-[1.39], and [1.13]-[1.47] colour pairs, as seen in Fig. 13. In this case, the mean colour difference is $0.36 \pm 0.008$ mag. This behaviour would be compatible with a coeval blue-red peak connection if the age metallicity and colour-metallicity relations were linear (or close to).

In this case, the lack of blue counterparts for the reddest, much less prominent, and presumably youngest peaks, at [1.60] and [1.69], would suggest that the formation of blue GCs may have ceased before the formation of these red GCs.

6 NGC 5128: AT THE OUTSKIRTS OF THE VIRGO SUPER-CLUSTER

NGC 5128, the nearest elliptical galaxy to the MW, is the dominant system in the Centaurus A Group. Adopting a distance of $\approx 4$ Mpc (Harris et al. 2004b), places this galaxy at $\approx 16$ Mpc from the centre of the Virgo Super-cluster.

The difficulties in disentangling its GCs system from the heavy field contamination are clearly described in Harris et al. (2004a), Harris et al. (2004b) and Woodley et al. (2010).

Recently, Hughes et al. (2021) have presented a comprehensive catalogue with 40502 GC candidates, using data from Gaia to remove field contaminants, and assign to each object a given total likelihood of being a genuine GC. As GCs in NGC 5128 are about three magnitudes brighter than those of their counterparts in NGC 4486, the inherent photometric errors are considerably smaller than in the last case. This allows a better recovery of colour structures using indices that include u magnitudes in their definition.

In particular, the Hughes et al. (2021) photometric catalogue gives (source by source) reddening corrected $(u-r)$ and $(r-z)$ colours for a sample of their GC candidates, taken from the NOAO – Source Catalog (NSC – DEC camera) (Nidever et al. 2018).

A comparison of the NSC colour relations with those from Table A2, shows identical slopes, and that the transformation to the SDSS system can be achieved through zero point shifts:

$$\begin{align*}
(r-z)_{SDSS} &= (r-z)_{NSC} + 0.09 \\
(u-r)_{SDSS} &= (u-r)_{NSC} - 0.06
\end{align*}$$

and hence:

$$(u-z)_{SDSS} = (u-z)_{NSC} + 0.03$$

with uncertainties of $\pm 0.01$ mag for each of the zero point shifts. These relations, were derived using the 1480 GC candidates inside 2° from the centre of NGC 5128, and are presented in Fig. A8. The elliptical contours in this figure correspond to a total likelihood larger than 0.50. This last figure also shows, as a reference, a sample of 511 GCs with measured radial velocities, and brighter than $g = 23.0$, in NGC 4486.

The $(u-z)$ GCCD for that sample clearly shows seven of the TVP components, with $\sigma_{(u-z)} = 0.021$ mag, as displayed in Fig. 20. The vertical lines indicate the expected position of the TVP components according to Table A3. This diagram also includes the output from the RSS routine after $5 \times 10^2$ random sampling cycles.

Adopting a limiting magnitude $r = 20.5$, decreases the photometric errors, and the sample size to 1080 GC candidates, making the pattern contrast more evident as seen in Fig. 21 (with $\sigma_{(u-z)} = 0.030$ mag).

![Figure 20](image)

The most clear definition of the colour pattern is displayed in Fig. 22. This case corresponds to 552 objects with a total likelihood parameter $> 0.85$, $r$ magnitudes from 18.0 to 20.5, and position angles from 0° to 270° (with $\sigma_{(u-z)} = 0.028$ mag).

In all the last figures, the smoothing kernel size was set to 0.070 mag (taking into account the slope of the $(u-z)$ vs. $(g-z)$ colours relation).

7 SUMMARY OF RESULTS

This section gives a description of the main results presented in this paper:

(i) The RSS approach confirms previous results and identifies a multi-peaked structure in the GCCD corresponding to a composite GCs sample in seventy one non-giant galaxies included in the ACSVs.

(ii) The combination of the statistical approach given by OA2016, and the $ugriz$ fits presented in this paper, produces a reliable sample of GC candidates within $R_{gal} = 60'$ in NGC 4486. The output from the RSS routine on this sample, leads to the identification of a clear multi-peaked pattern in an area $\approx 15$ times larger than that covered by the ACSVs data.

(iii) The TVP pattern is easily detected in the GCCD of cluster candidates with $R_{gal} < 5'$. This pattern is also detected in a sub-sample of confirmed GCs, with $(g-i)$ colours from Harris (2009), and radial velocities from Strader et al.
(2011). This result proves that the colour pattern is not a consequence of badly removed field contamination or eventual instrumental effects.

(iv) It must be stressed that none of the thirteen non-giant galaxies whose composite GC sample shows a strong pattern (see Fig. 2 and Fig. 3), is located within $R_{\text{gal}} =5\arcmin$. Most of these moderately bright galaxies are spread on an area with a radius of $5\arcmin$ from the centre of NGC 4486, i.e., the TVP seems present not only in the central regions, but over a large area in the Virgo cluster. Furthermore, the detection of the TVP features in NGC 5128, through data and membership analysis completely different to those presented in this paper, indicates that the TVP could be traced to the outskirts of the Virgo Super–cluster.

(v) According to the numerical models described in Section 2, the probability of a fortuitous coincidence between the GC colour pattern present in the non giant galaxies, and that found for the NGC 4486 clusters, being independent data sets, would be in the order of $2.5\times10^{-3}$. This probability decreases to $1.25\times10^{-4}$ if the case of NGC 5128 is included.

(vi) A bi-dimensional analysis, in the $(g-i)$ vs $(g-z)$ plane, indicates that the TVP can be detected inside $R_{\text{gal}} =45\arcmin$, i.e., neither sampling noise, nor colour gradients or the presence of an eventual competing pattern, affect its detectability on a large angular scale.

(vii) The $R_{\text{med}}$ and $R_{\text{90}}$ parameters show a continuous increase as GCs become bluer. The presence of a clear "glitch", or discontinuity, at $(g-z) \approx 1.15$, argues in favor of a bimodal scenario as those characteristics are indicative of two different GC (blue ad red) families, with distinctic spatial distributions. This behaviour is coherent with the signature of dissipative collapse in both the halo and bulge sub-populations. However, the prominent blue peak at $(g-z) =0.86$, similar to the dominant blue peak observed for GCs in Virgo galaxies fainter than $M_g =-19.0$ (see Fig. 4), would be consistent with cluster accretion from these less massive galaxies. Dry mergers, in particular, would preserve the TVP features, as they seem common to most galaxies.

(viii) Even though, individually, each of the TVP components seem to have null or very mild colour gradients, these gradients can arise when, in a given galactocentric range, the GC sample includes cluster sub-populations with different spatial scale lengths. For example Forbes & Remus (2018), have already noticed that, in some cases, blue GCs, if considered as a single sub-population, exhibit detectable colour gradients. These colour trends can be explained, as shown in Fig. 18, by the composition of the different blue sub-populations, that reach increasingly larger galactocentric radii as their colors become bluer.

(ix) Spectroscopic analysis of the GC chemical gradients in NGC 4486 has been presented by Villaume et al. (2020), who find a marked spread of the $[\text{Fe/H}]$ index over a large range of galactocentric radius, and also, "remarkably flat" galactocentric gradients for both blue and red cluster populations. In turn, Ko et al. (2022), obtain a mild gradient for red GCs, and a slightly steeper one characterizing the blue GCs population. These works have distinct $[\text{Fe/H}]$ scales but, in both

Figure 21. $(u-z)$ colour distribution for 1080 GC candidates with a likelihood > 0.5, brighter than $r =20.5$, and within $2\deg$ from the centre of NGC 5128, using data from Hughes et al. (2021). The smoothed colour distribution was obtained adopting a 0.07 mag Gaussian kernel. Vertical dashed lines correspond to the TVP pattern listed in Table A3. The blue line is the output from the RSS routine run on the GC sample included in Fig. 20. The original NSC colours have been transformed to the SDSS system by adding +0.03 mag (see text).

Figure 22. $(u-z)$ colour distribution for 552 GC candidates with a likelihood > 0.85, $r =18.0$ to 20.5 mag, position angles from $0\deg$ to $270\deg$, and within $2\deg$ from the centre of NGC 5128, using data from Hughes et al. (2021). The smoothed colour distribution was obtained adopting a 0.07 mag Gaussian kernel. Vertical dashed lines correspond to the TVP pattern listed in Table A3. The blue line is the output from the RSS routine run on the GC sample included in Fig. 20. The original NSC colours have been transformed to the SDSS system by adding +0.03 mag (see text).
cases, the mean difference between red and blue clusters is ≈0.75 dex. The clarification of the complex colour structure seen in the NGC 4486 clusters, in spectroscopic terms, will require more accurate metallicity determinations, as well as larger sampling volumes. For example, the total population brighter than $i = 22.0$ (or $g \approx 23.0$), inside $R_{gal} = 45'$, is ≈ 2800 GCs. Random sub-samplings of this population, including ten to twenty percent of these clusters (comparable to the size of the spectroscopic samples), leads to a rather unstable behaviour of the derived galactocentric colour gradients, and presumably, of the chemical abundances.

(xi) The total GC population with $R_{gal} < 60'$, assuming a fully Gaussian integrated luminosity function amounts to $14900 \pm 1100$. This last uncertainty is related with those of the $\alpha = 0.35 \pm 0.05$ and $\alpha = 0.030 \pm 0.01$ parameters, as well as that of the completeness within the photometric acceptability boundary, that ranges from 0.80 to 0.85.

This estimate of the total GCs population, derived on the basis of the identification of individual GC candidates, is in very good agreement with Durrell et al. (2014), who find 14520 ± 1200 GCs, through a different approach, based on GC areal density profiles of both blue and red GCs.

(xii) The complex stream-like structures seen in Fig. 10 deserve further attention in order to confirm that they are the result of merger events as those described by Romanowsky et al. (2012). We note that GCs associated with feature a, a confirmed stream, displays all the TVP colour peaks, as well as the other three similar structures (b, c, d). According to those last authors, streams of this type would be detectable over a time span of about 1 Gyr, i.e., they formed much later than the events that presumably imprinted the TVP on the whole GC population.

The case of NGC 5128, also indicates the need to revise the situation of GCs in Local Group galaxies. We note that a multi-peaked chemical abundance structure seems to be present in the inner regions of the MW, as reported by Bensby et al. (2017). That result was based on high resolution spectroscopy of dwarf and sub-giant stars observed during micro-lensing events. Even though the observed sample is small (about a hundred stars), it is remarkable that the multi-peaked chemical distribution remains stable as new data are added from subsequent events observed along the years.

A number of phenomena, like mergers of galaxies, or of sub-galaxy clusters, inducing star forming bursts, followed by rapid quenching originated by post nuclear SMBH activity at high redshifts, appear as promising mechanisms to elucidate the origin of the GCs colour pattern. The effects of multiple mergers, in a Millennium TNG scenario, have been in fact successful in reproducing some of the characteristics of GC systems (Ramos-Almendares et al. 2020).

Massive galaxies, as NGC 4486, have had presumably complex and distinct histories in terms of interactions and mergers, that would be eventually reflected by their GCCDs. However, the Template Virgo Pattern emerges as an indicator of a common phenomenon affecting the temporal GCs formation sequence in the Virgo cluster as a whole. The presence of a comparable pattern in the Fornax cluster, justifies a further study in this last, and in other galaxy clusters, in an attempt to clarify both the nature and the spatial scale of the mechanism leading to the GCs colour modulation.

8 CONCLUSIONS

The existence of a multi-peaked GCs colour pattern in Virgo, strongly suggests that the formation of these clusters is not a phenomenon restricted to a given galaxy but, at least in part, the consequence of a common and repetitive process working on supra-galactic spatial scales. The coincidence of the colour peaks in different galaxies requires that the chemical enrichment in these systems has proceeded at the same pace (although reaching different maximum values as a function of galaxy mass).

Definite conclusions about the physical nature of the putative phenomena that would modulate the GCCD (and possibly the chemical abundance distribution of the stellar populations in general) require a solid clarification of the relation between colours, ages and metallicities. Conflicting results are available in the literature concerning this last issue (Kim & Yoon 2017; Usher et al. 2019; Villaume et al. 2019; Fahrion et al. 2020; Kim et al. 2021).

The tentative approach presented in F2017 assumes a bi-furcated age-metallicity relation (as that observed in the MW) as a possible way to connect the effect of a given external event on both the blue and red GCs populations. This is an arguable assumption since a clear age-metallicity relation for GCs in other galaxies is not known.

With that caveat in mind, we note the results presented in this work, indicating that blue peaks seem mirrored by a red peak counterpart with a mean $(g - z)$ colour difference of 0.36 mag. Adopting, for example, the colour-metallicity relation presented by Villaume et al. (2019), that colour separation would translate to a metallicity difference of ≈ 0.70 dex. This chemical offset is comparable to that observed between the red and blue MW GCs age-metallicity sequences (Leaman et al. 2013; Massari, D. et al. 2019). On this basis, a possible connection between coeval blue and red TVP peaks cannot be dismissed.

The detection of the TVP features in the GCCD of NGC 5128 uncovers a connection between the Centaurus A Group and the Virgo cluster. This is a challenging situation regarding the identification of the physical phenomenon that would be eventually capable of originating a colour structure that is shared by GCs in galaxies currently separated by ≈ 16 Mpc.

ACKNOWLEDGEMENTS

This work is dedicated to Dr. Alejandro Feinstein, a pioneer in the field of stellar photometry and who, kindly and
generously introduced the author into the world of star cluster research. Thanks are due to Dr. Daniel Carpineto, for providing thoroughly tested random number generators used in the Monte Carlo models and RSS routines, and to Drs. Fávio Faifer and Carlos Escudero for useful comments about the manuscript.

REFERENCES

Ashman K. M., Zepf S. E., 1992, ApJ, 384, 50
Bellini A., et al., 2015, ApJ, 805, 178
Bensby et al., 2017, A&A, 605, A89
Bressan A., Marigo P., Girardi L., Salasnich B., Dal Cero C., Rubele S., Nanni A., 2012, MNRAS, 427, 127
Brodie J. P., Strader J., 2006, ARA&A, 44, 193
Chen C.-W., Côté P., West A. A., Peng E. W., Ferrarese L., 2010, ApJS, 191, 1
Doherty M., et al., 2009, A&A, 502, 771
Durrell P. R., et al., 2014, ApJ, 794, 103
Fahroin K., et al., 2020, A&A, 637, A27
Ferrarese L., et al., 2012, ApJS, 200, 4
Forbes D. A., Remus R.-S., 2018, MNRAS, 479, 4760
Forrest B., et al., 2020, ApJ, 903, 47
Forte J. C., 2017, MNRAS, 468, 3917
Forte J. C., Martínez R. E., Muzzio J. C., 1982, AJ, 87, 1465
Forte J. C., Faifer F. R., Vega E. I., Bassino L. P., Smith Castelli A. V., Cellone S. A., Geisler D., 2013, MNRAS, 431, 1405
Forte J. C., Vega E. I., Faifer F. R., Smith Castelli A. V., Escudero C., González N. M., Sesto L., 2014, MNRAS, 441, 1391
Forte J. C., et al., 2019, MNRAS, 482, 950
Harris W. E., 2009, ApJ, 703, 939
Harris G. L. H., et al., 2004a, AJ, 128, 712
Harris G. L. H., Harris W. E., Geisler D., 2004b, AJ, 128, 723
Harris W. E., Ciccone S. M., Eade G. M., Sneden C., 2011, ApJS, 180, 54
Jordán A., Peng E. W., Blakeslee J. P., Côté P., Eyheramendy S., Ferrarese L., 2015, ApJS, 221, 13
Kim S., Yoon S.-J., 2017, ApJ, 835, 101
Hughes A. K., et al., 2021, ApJ, 914, 16
Izumi T., et al., 2021, ApJ, 914, 36
Jordán A., et al., 2009, ApJS, 180, 54
Jordán A., Peng E. W., Blakeslee J. P., Côté P., Eyheramendy S., Ferrarese L., 2015, ApJS, 221, 13
Kim S., Yoon S.-J., 2017, ApJ, 843, 43
Kim S., Yoon S.-J., Lee S.-Y., Chung C., Sohn S. T., 2021, ApJS, 256, 29
Ko Y., et al., 2017, ApJ, 835, 212
Ko Y., et al., 2022, ApJ, 931, 120
Leaman R., VandenBerg D. A., Mendel J. T., 2013, MNRAS, 436, 122
Martín-Navarro I., Pillepich A., Nelson D., Rodriguez-Gomez V., Donnari M., Hernquist L., Springel V., 2021, Nature, 594, 187
Massari, D. Koppelman, H. H. Helmi, A. 2019, A&A, 630, L4
Muñoz R. P., et al., 2014, ApJS, 210, 4
Müller H. D., et al., 2020, MNRAS, 493, 3557
Romanowsky A. J., Strader J., Brodie J. P., Mihos J. C., Spitler L. R., Forbes D. A., Foster C., Arnold J. A., 2012, ApJ, 748, 29
Schrabback T., 2011, ApJ, 737, 103
Schulz C., Pfenninger A., Kroupa P., 2015, A&A, 582, A93
Sérsic J. L., 1968, “Atlas of Galaxies Australes”, Universidad Nacional de Córdoba, Argentina
Sobral D., Stroe A., Dawson W. A., Wittman D., Lee M. J., Röttgering H., van Weeren R. J., Brüggen M., 2015, MNRAS, 450, 630
Strader J., et al., 2011, ApJS, 197, 33
Stroe A., et al., 2015, MNRAS, 450, 646
Strom S. E., Forte J. C., Harris W. E., Strom K. M., Wells D. C., Smith M. G., 1981, ApJ, 245, 416
Tony C. L., Dressler A., Blakeslee J. P., Ajhar E. A., Fletcher A. B., Luppino G. A., Metzger M. R., Moore C. B., 2001, ApJ, 546, 681
Usher C., Brodie J. P., Forbes D. A., Romanowsky A. J., Strader J., Pfeffer J., Bastian N., 2019, MNRAS, 490, 491
Valein D., Bernal J. L., Jimenez R., Verde L., Wandelt B. D., 2020, Journal of Cosmology and Astroparticle Physics, 2020, 002
Villaume A., Romanowsky A. J., Brodie J., Strader J., 2019, ApJ, 879, 45
Villaume A., Foreman-Mackey D., Romanowsky A. J., Brodie J., Strader J., 2020, ApJ, 900, 95
Villegas D., et al., 2010, ApJ, 717, 603
Wagner-Kaiser R., et al., 2017, MNRAS, 471, 3347
Woodley K. A., Gómez M., Harris W. E., Geisler D., Harris G. L. H., 2010, AJ, 139, 1871
Wu Y., et al., 2022, ApJ, 926, 149

APPENDIX A: COLOUR-COLOUR RELATIONS, GLOBULAR CLUSTER CANDIDATES IDENTIFICATION, AND ADDITIONAL FIGURES AND TABLES

A1 Photometric data sources

A brief description of the papers with photometric data relevant to this work, follows:

(i) Integrated colours, based on $ugriz$ magnitudes in the SDSS (DR5) system, have been presented by Chen et al. (2010) for galaxies in the Virgo cluster. In this sample, sixty galaxies are brighter than $g\ =14.0$, and their colours, in a galactocentric radius range from 1.0 to 10.0$''$ were adopted to define the multicolour reference frame.

(ii) Strader et al. (2011) published radial velocities for a sample of 735 GCs associated with NGC 4486. These authors also present $griz$ magnitudes, taken from CFHT/Megacam observations by Harris (2009), but calibrated to the SDSS (DR7) system.

(iii) $griz$ Gemini and $(C-T_1)$ photometry for 521 GC candidates in a GMOS field, $5''$ to the south of the NGC 4486 centre, was presented in Forte et al. (2013). This paper introduced a photometric approach to identify GCs based on pseudo-continuum fits defined by $C-griz$ magnitudes. The same method, adopted in the present work, replaces $C$ magnitudes (Washington system) by a magnitude as defined in the SDSS system.

A2 Colour-colour relations and $ugriz$ pseudo-continuums

The zero points of the photometric data given in Strader et al. (2011), Forte et al. (2013), and Oldham & Auger (2016) were shifted to agree with the Chen et al. (2010) colours, according to the values listed in Table A1, and combined to define a multicolour reference frame. This was achieved by means of a bi-dimensional piece-wise analysis of each of the forty five colour-colour relations that can be defined in terms of the $ugriz$ magnitudes.

The linear piece-wise analysis detects two mild changes in some colour-colour slopes at $(g-i) =0.90$ and $1.10$ or $(g-z) =1.08$ and $1.35$, and in all cases, the linear fits included three colour segments

MNRAS 000, 1–18 (2022)
defined by these values, i.e. \((g - i)\) bluer than 0.90, \((g - i)\) from 0.90 to 1.10, and \((g - i)\) redder than 1.10.

The colour-colour relations were used to derive the ugriz pseudo-continuums, listed in Table A2 as a function of the \((g - i)\) colour (in 0.001 mag intervals). In this table, \(g\) magnitudes were arbitrarily set to \(g = 15.0\). All the colour-colour relations can be derived from this table.

**A3 Globular cluster candidates and field objects**

Oldham & Auger (2016) present ugriz photometry based on their own treatment of NGVS data for objects in a field centred on NGC 4486. This catalogue is used for the analysis presented in this work, after transforming their ugriz colours to the SDSS system. This was achieved in three steps:

First, by approximating the NGVS magnitudes to those of the SDSS system through the initial zero point shifts listed in Table 1. These shifts give a first approximation to the colour-colour relations defined in terms of the ugriz magnitudes for both systems. Secondly, adopting the relations between the NGVS and SDSS photometric systems presented by Ferrarese et al. (2012).

Finally, small corrections \((u : -0.03; g : +0.01; r : -0.03; i : -0.01; z : -0.02)\), were applied in order to satisfy all the colour-colour relations mentioned in the previous subsection. A problem with the zero point of the \(u\) magnitudes, for objects with \(R_{\text{gal}} > 10'\), is commented below.

GC candidates were identified by comparing their ugriz magnitudes, with the pseudo-continuum in Table A2. A similar approach was presented in Forte et al. (2013) although, in the present work, the proximity is defined by the minimum \(\text{rms}\) of the pseudo-continuum fits. This quantity is a function of apparent magnitude as photometric errors increase for fainter objects. Magnitude fit residuals for each filter band \(i\) are defined as:

\[
\epsilon_i = [m_i - (m_{\text{table}} + \Delta_i)] / \omega_i \tag{A1}
\]

where each magnitude difference is weighted with \(\omega_i\), the inverse of the photometric \(\text{rms}\) values given in OA2016, for each magnitude \(m_i\). In this equation, \(\Delta_i\) is the mean difference between the observed magnitudes and those in Table A2, that define the pseudo-continuum delivering the minimum \(\text{rms}\) of the \(\epsilon_i\) residuals.

It must be taken into account that, besides the contribution of photometric errors, the \(\text{rms}\) values will reflect the effect of possible differences between the reference ugriz pseudo-continuums and those that characterize a given GC. These differences may arise as a consequence of different horizontal branch morphologies, ages, or the presence of multiple stellar populations.

A quantitative boundary, separating GCs and field objects, was determined by analysing the behaviour of the \(\text{rms}\) values as a function of the \(g\) magnitudes. This was accomplished by means of GCs with radial velocities from ST2011, and objects with a probability \(P > 0.90\) of being a genuine blue or red GC with \(R_{\text{gal}} < 10'\).

The analysis shows that the limiting boundary between GC candidates and field objects, can be approximated as:

\[
\delta = a e^{\alpha(g - g*)} \tag{A2}
\]

with \(\alpha = 0.35 \pm 0.05\), \(a = 0.03 \pm 0.005\), for \(g > g*\), and \(\delta = a\) for \(g < g*\); with \(g* = 21.5\).

This boundary contains 85 percent (within \(R_{\text{gal}} = 10'\)) to 80 percent (at larger \(R_{\text{gal}}\)) of the GC candidates.

Fig. A1 shows the behaviour of the \(\text{rms}\) of the \(\epsilon_i\) residuals as a function of \(g\) magnitudes, and the domain of both GC candidates (black dots) and field interlopers (cyan dots) for a total of 13172 objects inside \(R_{\text{gal}} = 60'\).

In turn, Fig. A2 and Fig. A3 display the fit residuals of the ugriz magnitudes, as a function of \((g - z)\) colours and \(g\) magnitudes, respectively, for 511 GCs with radial velocities from ST2011. These diagrams show no systematic residuals with GC colours, brightness, or galactocentric radii, indicating that the ugriz pseudo-continuums listed in Table A2, provide a good representation of the cluster colours. In this process, we noted that \(u\) magnitudes, in particular, do show a systematic difference in the sense that GCs with \(R_{\text{gal}} > 10'\) are 0.09 mag fainter than those in the inner region.

This difference appears as a marked feature, more compatible with a photometric zero point shift than with the effect of a physical gradient. Ultraviolet magnitudes for objects outside \(R_{\text{gal}} = 10'\) were then corrected by \(-0.09\) mag. The final magnitude residuals as a function of \(R_{\text{gal}}\) are shown in Fig. A4.

Fig. A5 shows the relation of the TVP peaks found in the SDSS and ACS/SDSS systems vs. those in the NGVS system. This diagram shows no significant differences between the colours of the peaks detected in the first two systems.

Fig. A6 depicts the GCCD for 6817 objects considered as field interlopers within 60' from the centre of NGC 4486.

**A4 GCCD in three glactocentric radius ranges in NGC 4486**

The smoothed \((g - z)\) colour distribution for a total of 3128 GC candidates in three different galactocentric ranges \((0.5'\) to \(5', 5'\) to \(14'\) and \(14'\) to \(45'\)) is shown in Fig. A7.

**A5 \((u-z), (r-z)\) and \((u-r)\) colour relations for GCs in NGC 5128**

Fig. A8 displays the \((u - z)\) vs. \((r - z)\) and \((u - r)\) colour relations for GCs in NGC 5128, using data from Hughes et al. (2021), once transformed to the SDSS system through zero point shifts (see text).
Figure A1. \textit{rms} of the fit residuals, $\epsilon_i$, as a function of $g$ magnitudes for 13271 objects within 60$'$ from the centre of NGC 4486. Black dots are considered as GC candidates. Cyan dots are classified as field objects.

Table A1. Adopted ugriz zero point shifts.

| Source | u    | g    | r    | i    | z    |
|--------|------|------|------|------|------|
| ST2011 | —    | 0.00 | -0.01| 0.00 | —    |
| FO2013 | —    | 0.02 | 0.03 | 0.00 | -0.06|
| OA2016 | 0.35 | 0.13 | 0.02 | 0.03 | 0.00 |

Table A2. Globular cluster ugriz pseudo-continuums as a function of the (g-i) colour (complete table in the electronic version of the paper).

| (g-i) | u  | g   | r   | i   | z   |
|-------|----|-----|-----|-----|-----|
| 0.600 | 15.759 | 15.000 | 14.554 | 14.400 | 14.313 |
| 0.601 | 15.761 | 15.000 | 14.553 | 14.399 | 14.311 |
| 0.602 | 15.762 | 15.000 | 14.553 | 14.398 | 14.310 |

Figure A2. Colour residuals from the ugriz fits to photometric data of 511 GCs with measured radial velocities as a function of $(g-z)$ colour. Each set of residuals is arbitrarily shifted by 0.2 mag. in ordinates.

Figure A3. Magnitude residuals from the ugriz fits to photometric data of 511 GCs with measured radial velocities as a function of $g$ magnitudes. Each set of residuals is arbitrarily shifted in ordinates.
Synchronized Globular Cluster Formation

Figure A4. Magnitude residuals from the $ugriz$ fits to photometric data of 511 GCs with measured radial velocities as a function of galactocentric radii (in arcmin). Each set of residuals is arbitrarily shifted in ordinates.

Figure A5. Correlations between the $(g - z)$ colours of the peaks detected in the SDSS system (open dots), and in the ACSV S system (filled dots) with those found on the NGVS data. The blue line is the SDSS-NGVS relation presented in Section 3. The red line corresponds to that derived by Wu et al. (2022) (shifted by +0.015 mag in ordinates).

Figure A6. Smoothed $(g - z)$ colour distribution for 6817 objects within 60′ from the centre of NGC 4486 and considered as field interlopers. The blue line is the scaled down output from the RSS routine for GC candidates. Dashed lines correspond to the TVP colours.

Figure A7. Smoothed $(g - z)$ colour distributions for 3128 GC candidates in three different galactocentric ranges. The red line belongs to: $R_{gal} = 0.5$ to 5′; black line: 5 to 14′; and blue line: 14 to 45′ (see text). Dashed lines correspond to the TVP colours listed in Table A3. Red, black and blue dots indicate colour peaks found in each galactocentric sample.
Figure A8. \((u-z)\) colour vs. \((r-z)\) (left) and \((u-r)\) (right) for 1480 GC candidates with a likelihood larger than 0.50, in NGC 5128 (blue dots) from Hughes et al. (2021). As a reference, green dots are 511 GCs with radial velocities in NGC 4486, from Strader et al. (2011). The black lines are the colour relations derived from Table A2.

Table A3. Template Virgo Pattern in three SDSS colour indices.

|    | (g-i)  | (g-z)  | (u-z)  |
|----|--------|--------|--------|
| 0.62 | 0.72   | 1.52   |
| 0.72 | 0.85   | 1.82   |
| 0.78 | 0.93   | 2.01   |
| 0.86 | 1.03   | 2.25   |
| 0.93 | 1.13   | 2.48   |
| 0.99 | 1.21   | 2.67   |
| 1.05 | 1.29   | 2.85   |
| 1.12 | 1.39   | 3.08   |
| 1.18 | 1.47   | 3.26   |
| 1.27 | 1.60   | 3.55   |
| 1.33 | 1.69   | 3.76   |