Abstract. Observational and theoretical arguments support the idea that violent events connected with AGN activity and/or intense star forming episodes have played a significant role in the early phases of galaxy formation at high red shifts. Being old stellar systems, globular clusters seem adequate candidates to search for the eventual signatures that might have been left by those energetic phenomena. The analysis of the colour distributions of several thousands of globular clusters in the Virgo and Fornax galaxy clusters reveals the existence of some interesting and previously undetected features. A simple pattern recognition technique, indicates the presence of "colour modulations", distinctive for each galaxy cluster.

These patterns were first found on composite samples of globular clusters in galaxies with $M_g = -20.2$ to -19.2, and later, detected on some subsamples of globular associated with individual giant elliptical galaxies. The results suggest that the globular cluster formation process has not been completely stochastic but, rather, included a significant fraction of globulars that formed in a synchronized way and over supra-galactic spatial scales. A tentative approach indicates that the putative events that enhanced globular cluster formation took place during a time lapse of 1.5 Gyr and in a range of red shifts $z$ between 2 and 4.

1. Introduction.

Being old stellar systems, and potential carriers of valuable information of the astrophysical processes that characterized the early Universe, globular clusters (GCs) have become the target of an increasing volume of research on both the observational and theoretical fronts.

Even so, some historical questions are still open. For example, why GC formation is not detected in low red shift galaxies even though enough interstellar matter is available to fuel such a process? Which is the "missing" ingredient not operating at low red shifts? Nearby galaxy mergers do exhibit some massive clusters that seem to resemble young globulars and suggest that violent/energetic phenomena might be such an ingredient.

A key subject in the study of globular cluster systems is the analysis of the globular cluster colour distribution (GCCDs in what follows). A proper decoding of these distributions imply the understanding of the connection between ages, chemical abundances and spatial distributions.
Frequently, these distributions exhibit the so-called "colour bimodality", i.e., the presence of two dominant ("blue" and "red") GC populations. Peng et al. (2006) have shown that bimodality is in fact a feature that depends on galaxy mass. The red GC population becomes less evident with decreasing mass and disappears in the less massive galaxies. In turn, "blue" globulars seem to be present in almost all galaxies.

This characteristic led Cen (2001) to suggest that blue globulars formed in a synchronized way and as the result of a very large scale phenomenon: The re-ionization of the Universe. An underlying question is, if other highly energetic events might have left some kind of detectable features, for example, on the GCCDs.

Fabian (2012) presents a number of observational results that point out the important role of AGN activity in producing massive outflows that change the environmental conditions of interstellar gas on large spatial volumes. On the other side, the most recent models of galaxy formation (e.g. Vogelsberger 2014) include AGN phenomena and lead to remarkably realistic results.

In general, these phenomena are expected to produce star forming "quenching". However, several results in the literature argue in the other direction, i.e., that under given circumstances, these effects end up in enhancing the star forming process (see, for example, Silk 2013).

In the particular case of GCs, and in a naive approach, one might expect that quenching/enhancement would be reflected as valleys/peaks in the GCCDs. So far these kind features have not been reported.

Eventually, this situation may suggest that the usual approach in analysing the GCCDs needs a change in the strategy. For example, the composite samples of GCs belonging to galaxies with comparable brightness (mass) will presumably erase the characteristics of a given globular cluster system but, on the other side, might enhance the presence of systemic features common to these galaxies.

This type of approach is the core of the following analysis. The details of the pattern recognition procedure, as well as other inherent results, can be found in Forte (2017; MNRAS, submitted).

2. Data Sources

The main data source in this work is the $g, z$ photometry for GCs associated with galaxies in the Virgo and Fornax clusters presented by Jordán et al. (2006, 2015). We also revisit the Washington photometry given by Forte, Faifer & Geisler (2007) for the central giant galaxies NGC 1399 and NGC 4486 and, in the case of this galaxy, the $griz$ Gemini − GMOS photometry by Forte et al. (2013).

We adopt a GCs limiting magnitude $g = 25.0$ in order to guarantee both a high spatial completeness and $(g − z)$ colour errors below $≈ 0.07$ mag. In summary, these data correspond, to 7671 GCs in 88 Virgo galaxies and 4317 GCs in 42 Fornax galaxies.

Fig. 1 shows the colour magnitude diagram for the Virgo and Fornax galaxies. Galaxies above the solid horizontal line are considered as giants. The dashed horizontal line is the faintest limit of the analysis.
3. Colour patterns recognition.

The usual analysis of GCCDs stands on discrete-bin colour histograms and/or smoothed versions of these histograms. These last "generalized" histograms are obtained by convolving the colour data with, for example, Gaussian kernels. In this work we adopt the same tools but, instead of sampling a single galaxy, we define a moving sampling window (0.4 mag. wide in galaxy absolute magnitude) and combine all the GCs associated with galaxies within that window. In turn, this window moves in steps $\delta = 0.20$ mag.

A composite GCCD is obtained for each galaxy sample, and a routine searches for colour peaks and valleys (i.e. colours where $[dN/d(g-z)] = 0$). This procedure was carried out for all galaxies fainter than $M_g = -20.2$ (i.e. non-giant galaxies), leading to the identification of 231 peaks in Virgo and 179 in Fornax. The statistics of these peaks define a first approach to the Virgo and Fornax colour patterns.

A further analysis reveals that most of these patterns appear for GCs associated to galaxies with absolute magnitudes $M_g$ from -20.2 to -19.2.

The composite GCCDs for 13 Virgo galaxies and 7 Fornax galaxies are shown (both in the discrete and smoothed histogram format) in Fig. 2 and Fig. 3 respectively. In these figures, the discrete-bin histograms have 0.04 mag bins while, the smoothed distributions were obtained with a Gaussian kernel $\sigma_{(g-z)} = 0.015$ mag. Dashed lines indicate the respective colour patterns and solid dots identify the features found by the peak finding routine.

It is worth mentioning that colour patterns seen in these diagrams survive when the GC samples are divided in terms of galaxy groups or in terms of the apparent magnitudes of the clusters.

Within the $(g - z)$ colour range covered by old GCs (0.75 to 1.65), the Virgo galaxies exhibit six (and possibly seven) colour peaks while five (and possibly 6) are detectable in Fornax galaxies.

4. Colour patterns in Virgo Giants.

In this, and in the following section, we present the results for the giant galaxies in both clusters. In what follows, all the diagrams display the smoothed GC colour distributions and the discrete-bins histograms (arbitrarily shifted upwards).

A remarkable object in Virgo is the giant galaxy NGC 4486 which has an extremely rich GC system (with about 15,000 clusters). In this case the routine searches for colour patterns within given ranges of galactocentric radii and position angles. These patterns are then compared with the corresponding reference pattern (Virgo or Fornax).

An example of the results for NGC 4486 is displayed in Fig. 4. This diagram shows eight coincidences with the colour pattern defined by GCs in fainter galaxies, without requiring any systematic shift in colour.

In fact, the routine finds the Virgo pattern in all the ten giant galaxies shown in Fig. 1 although, in most cases, colour shifts ranging from -0.05 to 0.01 mag. are required for a proper match with the reference pattern.

The composite GCCD for these giant galaxies is shown in Fig. 5. The colour
Figure 1. Absolute magnitude vs. \((g-z)\) colour for galaxies in the Virgo (filled circles) and Fornax (open circles) ACSs. Objects above the horizontal line are giant galaxies. The dashed line indicates the faintest limit of the analysis.

Figure 2. Discrete and smoothed colour distribution for 1531 clusters in 13 Virgo galaxies with \(M_g = -20.2\) to \(-19.2\). The dashed lines indicate the Virgo colour pattern.

distribution is broadly bimodal and the finding routine delivers a number of rather "incoherent" colour peaks (shown as dots). However, if the GCCD in each galaxy is shifted in colour, as indicated by the routine, and then added, the Virgo pattern appears clearly defined as depicted in Fig. 6.
Figure 3. Discrete and smoothed colour distribution for 1620 clusters in 7 Fornax galaxies with $M_g = -20.2$ to -19.2. The dashed lines indicate the Fornax colour pattern.

Figure 4. GC sample in NGC 4486. The sample includes 547 clusters with galactocentric radii from 0 to 110 arcsecs and position angles between 20 and 160 degrees. The dashed lines indicate the Virgo colour pattern.

5. Colour patterns in Fornax Giants.

In the case of the Fornax cluster, the dominant elliptical galaxy is NGC 1399. In this galaxy the routine indicates a colour shift of 0.035 in order to match the Fornax pattern as displayed in Fig. 7. Furthermore, the same shift is necessary when GCs in the four brightest giants in Fornax are combined. This result is shown in Fig. 8. This diagram shows seven out of eight possible coincidences with the Fornax pattern.
Figure 5. Composite GC colour distribution for 4974 clusters in ten giant Virgo galaxies. The dashed lines indicate the Virgo colour pattern. Dots indicate the position of (incoherent) colour peaks identified by the finding routine.

Figure 6. Composite GC colour distribution for 4974 clusters in ten giant Virgo galaxies. The dashed lines indicate the Virgo colour pattern. The individual colour patterns for GCs in each galaxy were shifted according to the results derived with the peak finding routine and then added (see text). The Virgo colour pattern is easily recognizable on the composite GCCD.

This last diagram does not includes NGC 1316, a galaxy with a complex multi-population GC system (see Sesto, Faifer and Forte, 2017). However, even in
Figure 7. GC sample in NGC 1399. The sample includes 663 clusters with galactocentric radii from 0 to 90 arcsecs and position angles between 0 and 360 degrees. The dashed lines indicate the Fornax colour pattern.

Figure 8. Composite GC colour distribution for 1677 clusters in four giant Fornax galaxies, shifted by 0.035 in the ($g - z$) colour. The dashed lines indicate the Fornax colour pattern.

This galaxy, some of the colour peaks in the Fornax pattern can be recognized as depicted in Fig. 9.

It is worth mentioning that the Washington ($C - T_1$) colours of clusters in NGC 1399 and NGC 4486 (Forte et al. 2007) show the same features detected on the ACS photometry.

The Virgo pattern is also recognizable in a peripheral field of NGC 4486 observed with Gemini—GMOS and includes some 500 GC candidates. (Forte et al 2013).
6. Conclusions.

A remarkable outcome in this work is that, once the colour patterns where recognized on the composite GCCDs of clusters associated with galaxies fainter than \( M_g =-20.2 \), the same features were later found in the individual GCCDs of giant galaxies both in Virgo and Fornax. This fact supports the physical entity of the colour patterns and argues against the idea that they are mere statistical fluctuations.

The origin of these colour patterns is intriguing and, at this stage, only speculative. There are different scenarios that deserve further research in order to clarify this situation. Among them, the effects of AGN activity or those connected with violent star formation events (e.g. arising in the merging of sub-cluster structures at high red shifts).

The clusters arising in these events may co-exist with other GCs that were formed along the individual life of a given galaxy. The rich GCs in giant galaxies may in fact hide the presence of those clusters although they are still detectable through the pattern recognition technique.

For galaxies fainter than \( M_g =-18.8 \), the colour patterns are not easily recognizable, except in a few cases. These systems do not have a significant population of intermediate colours and red GCs to allow the eventual presence of the colour patterns.

If chemical abundance correlates with time, as in the case of MW globulars (see Leaman, 2013), the different colour peaks may be indicating the time of the occurrence of “outer stimuli” that led to the enhancement of GC formation on \( Mpc \) spatial scales.

The adoption of the MW age-chemical abundance relation, just as a reference (and with all the well known caveats), suggests a time lapse of about 1.5 \( gy \),
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at red shifts \( z \) between 2 and 4, as the ages of those putative highly energetic events. Further characterization of these patterns in an astrophysical context will require high quality photometry and spectroscopy.

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