

# Globular clusters as tracers of the halo assembly of nearby central cluster galaxies

Michael Hilker<sup>1</sup> and Tom Richtler<sup>2</sup>

<sup>1</sup>European Southern Observatory, Karl-Schwarzschild-Str. 2,  
D-85748, Garching bei München, Germany  
email: [mhilker@eso.org](mailto:mhilker@eso.org)

<sup>2</sup>Departamento de Astronomía, Universidad de Concepción, Concepción, Chile  
email: [tom@astroudec.cl](mailto:tom@astroudec.cl)

**Abstract.** The properties of globular cluster systems (GCSs) in the core of the nearby galaxy clusters Fornax and Hydra I are presented. In the Fornax cluster we have gathered the largest radial velocity sample of a GCS system so far, which enables us to identify photometric and kinematic sub-populations around the central galaxy NGC 1399. Moreover, ages, metallicities and  $[\alpha/\text{Fe}]$  abundances of a sub-sample of 60 bright globular clusters (GCs) with high S/N spectroscopy show a multi-modal distribution in the correlation space of these three parameters, confirming heterogeneous stellar populations in the halo of NGC 1399. In the Hydra I cluster very blue GCs were identified. They are not uniformly distributed around the central galaxies. 3-color photometry including the *U*-band reveals that some of them are of intermediate age. Their location coincides with a group of dwarf galaxies under disruption. This is evidence of a structurally young stellar halo “still in formation”, which is also supported by kinematic measurements of the halo light that point to a kinematically disturbed system. The most massive GCs divide into generally more extended ultra-compact dwarf galaxies (UCDs) and genuine compact GCs. In both clusters, the spatial distribution and kinematics of UCDs are different from those of genuine GCs. Assuming that some UCDs represent nuclei of stripped galaxies, the properties of those UCDs can be used to trace the assembly of nucleated dwarf galaxies into the halos of central cluster galaxies. We show via semi-analytical approaches within a cosmological simulation that only the most massive UCDs in Fornax-like clusters can be explained by stripped nuclei, whereas the majority of lower mass UCDs belong to the star cluster family.

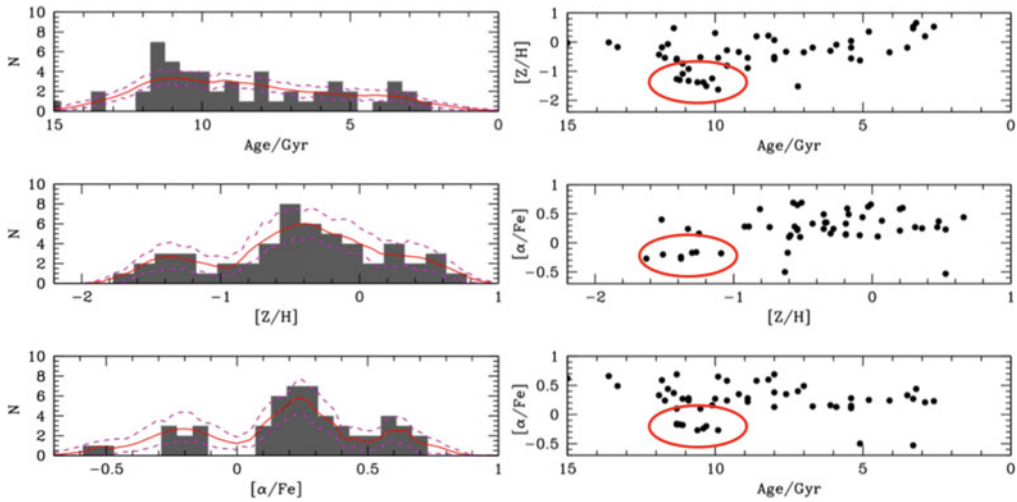
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## 1. Introduction

Central cluster galaxies host systems of thousands of globular clusters (GCs) which populate their halos out to several tens of effective radii. They are good probes to trace the assembly history of the diffuse and extended stellar halos residing in the cores of galaxy clusters. The colors and spectral line indices of GCs can be used to identify and characterize sub-populations of metal-poor and metal-rich as well as young GCs. Together with kinematic information from large radial velocity samples of GCs one can reconstruct the assembly history of different halo components.

The most nearby galaxy clusters, for which their central GC systems (GCSs) have been photometrically and/or spectroscopically studied in detail, are Virgo (e.g., Durrell *et al.* 2014, Romanowsky *et al.* 2012), Fornax (e.g., Bassino *et al.* 2006, Schuberth *et al.* 2010), Hydra I (e.g. Hilker 2002, Misgeld *et al.* 2011, Richtler *et al.* 2011), and Centaurus (e.g., Hilker 2003, Mieske *et al.* 2009). The number of radial velocity confirmed GCs around the central galaxies reaches 1000 GCs for M87 in Virgo and NGC 1399 in Fornax. The



**Figure 1.** Left panels: distribution of ages, metallicities and  $[\alpha/\text{Fe}]$  abundances for  $\sim 50$  Fornax GCs with high S/N spectroscopy. Right panels: correlations of the three parameters shown in the left. A distinct 'chemical' sub-group is highlighted by a red ellipse.

central GCSs are characterized by bimodal color distributions. Blue GCs are commonly interpreted to be metal-poor, and due to their extended spatial distribution are regarded as good tracers of the old, metal-poor halo of the central galaxies.

The high mass end of the GC mass function is dominated by so-called ultra-compact dwarf galaxies (UCDs), which first have been discovered in the core of the Fornax cluster (Minniti *et al.* 1998, Hilker *et al.* 1999, Drinkwater *et al.* 2000). It is under debate, which fraction of UCDs originate from stripped nucleated (dwarf) galaxies. The kinematic and stellar population properties of stripped nuclei-UCDs can be used to constrain the contribution of disrupted satellite galaxies to the build-up of central cluster galaxy halos. The most convincing case of a stripped nuclei origin of a UCD is the discovery of a supermassive black hole in M60-UCD1, one of the most massive and densest UCDs in the Virgo cluster (Seth *et al.* 2014). The supermassive black hole comprises 15% of the UCD's total mass.

## 2. The globular cluster system of the Fornax cluster

The Fornax cluster has a very well studied GC population. GC counts from photometric surveys revealed that there exist  $\sim 6,450 \pm 700$  GCs within 83 kpc projected distance around the central cluster galaxy NGC 1399 (Dirsch *et al.* 2003). Within 300 kpc of NGC 1399 the GC number counts increase to  $\sim 11,100 \pm 2,400$  GCs (Gregg *et al.* 2009, derived from the data of Bassino *et al.* 2006). The color distribution of GCs in Fornax is bimodal. The spatial distribution of red (mostly metal-rich) GCs follows the light of the central galaxy, whereas blue (mostly metal-poor GCs) are more widely distributed, suggesting that they trace the more extended halo population of NGC 1399.

Schuberth *et al.* 2010 analysed the kinematics of  $\sim 700$  GCs around NGC 1399 out to 80 kpc. They found that bimodality also exists in the kinematic properties of red and blue GCs. Red GCs are 'well-behaved', showing a gently decreasing velocity dispersion profile with increasing galactocentric distance. In contrast, blue GCs have a generally higher velocity dispersion at all distances with apparent substructures in the velocity vs. distance diagram. This might be an imprint of recent galaxy interaction or merging events

that leave accreted (mostly blue) GCs unmixed in phase space. Possible donor galaxies of accreted halo GCs are the nearby giant early-type galaxies NGC 1404 (see simulations by Bekki *et al.* 2003) and NGC 1387, but also dwarf galaxies that got entirely disrupted.

New spectroscopic surveys of GCs in the core region of the Fornax cluster are being analysed. A large VLT/VIMOS multi-object survey (PI: Capaccioli) covering the central square degree of the cluster will more than double the sample of radial velocity members. This will allow us to search for kinematic substructures in the halo of NGC 1399.

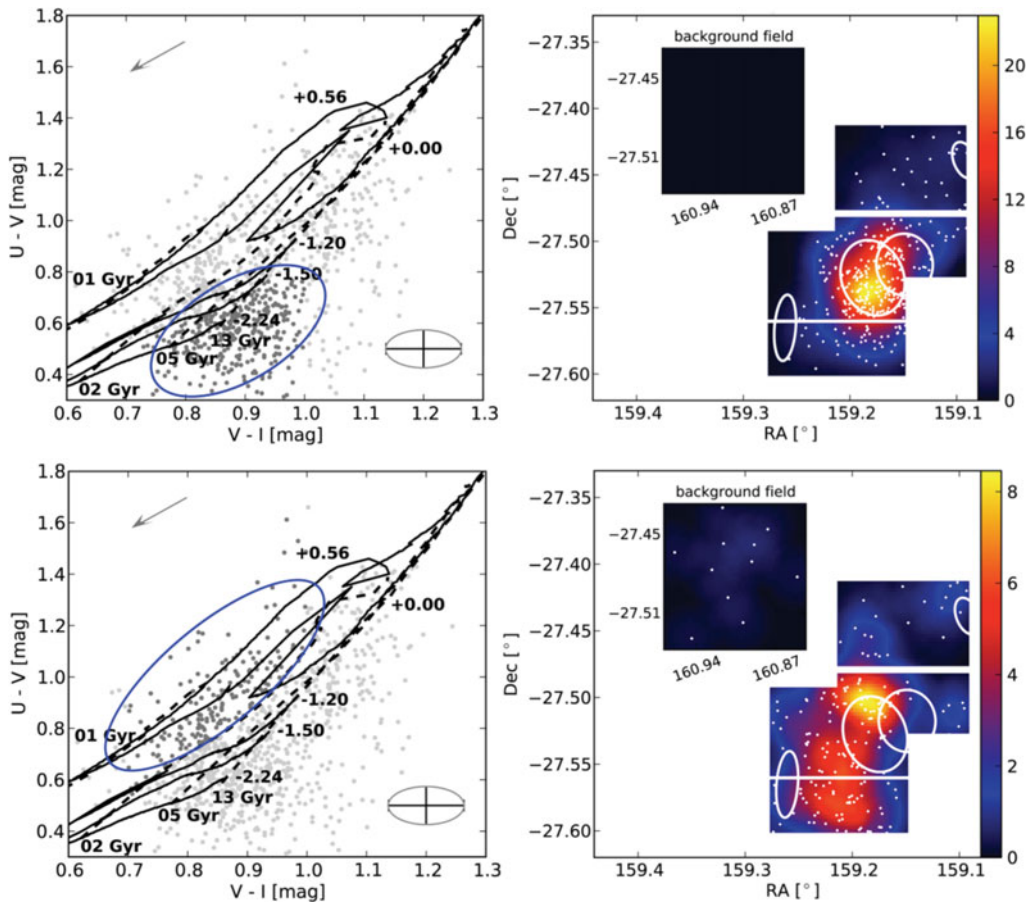
Deep VLT/FORS2 spectroscopy on  $\sim 50$  bright GCs ( $M_V < -9$  mag) allowed us to measure Lick indices and thus derive their ages, metallicities and  $[\alpha/\text{Fe}]$  abundances (Hilker, Puzia, *et al.*, in preparation). In Fig. 1 we show the distributions and correlations of these three quantities. Besides very old GCs there also exist a sizable number of metal-rich intermediate-age GCs (2-7 Gyr). And a striking feature in the correlation plots is a distinct group of seven old metal-poor GCs with sub-solar  $[\alpha/\text{Fe}]$  abundances. These GCs are restricted in projected galactocentric distance to NGC 1399 to a range of 18-31 kpc, five of them even to a range of 21-26 kpc, and thus might represent a ‘chemo-dynamical sub-group’ pointing to a common progenitor galaxy. Further kinematic analysis and correlations in phase space have to show whether this statement holds true.

### 3. Blue and blue globular clusters in the Hydra I cluster

The central galaxy NGC 3311 of the Hydra I cluster possesses a very rich GCS ( $\sim 16,000$  GCs, Wehner *et al.* 2008) and a large population of UCDs (Misgeld *et al.* 2011). Dynamical analysis of 118 bright GCs and the light around NGC 3311 revealed a steeply rising velocity dispersion profile, reaching values of  $800 \text{ km s}^{-1}$  at 100 kpc galactocentric distance (Richtler *et al.* 2011), comparable to the velocity dispersion of the cluster galaxies. This might either point to a massive dark halo around NGC 3311 or indicate kinematic substructure in the halo that mimics a dark halo.

Hilker (2002, 2003) noticed that there exist very blue GC candidates around NGC 3311, with  $0.70 < (V - I) = 0.85$  mag, much bluer than the blue peak of metal-poor GCs ( $(V - I)_{\text{blue}} = 0.9$ ). Those GCs are not centred on the galaxy but show an offset towards the north-east. Their blue  $(V - I)$  color can be interpreted in two ways. Either these GCs are old but very metal-poor, with  $[\text{Fe}/\text{H}] \simeq -2.5$  dex, or they are metal-rich but rather young (1-5 Gyr). In order to break the age-metallicity degeneracy in the  $(V - I)$  color, and thus uncover the nature of those blue GCs, we took  $U$ -band images in the cluster core with FORS at the VLT. In Fig. 2 we show the distribution of GCs in the  $(U - V)$ - $(V - I)$  2-color diagram (left panels). With help of the PARSEC model grid for single stellar populations (Bressan *et al.* 2012) one can select GCs of different ages and/or metallicities and study their spatial distributions (right panels in Fig. 2). Whereas old GCs are mostly centred on NGC 3311, the distribution of young GCs ( $< 2$  Gyr) is totally different. Most of them are displaced towards the North, coinciding with the location of a group of dwarf galaxies (Misgeld *et al.* 2008). Others are located south-east of NGC 3311 in the wake of the spiral galaxy NGC 3312, which is cruising through the Hydra I cluster at high speed, as evidenced by its compressed eastern edge.

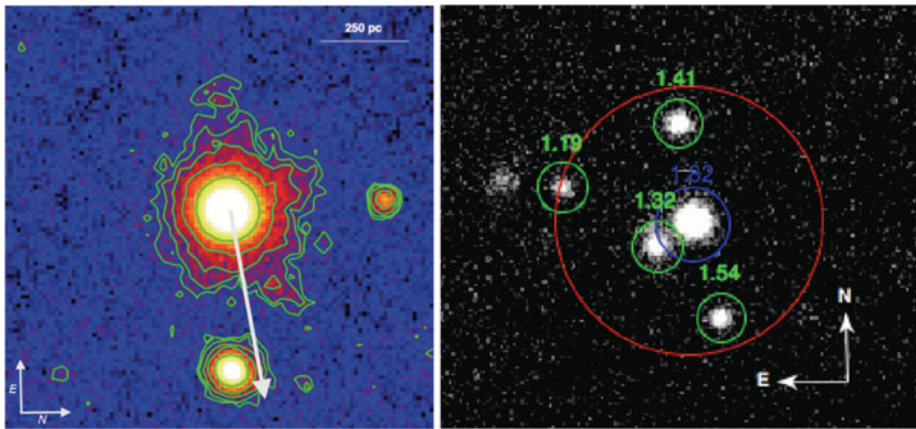
The offset distribution of young, blue GCs coincides with the location of an offset faint stellar envelope around NGC 3311 (Arnaboldi *et al.* 2012), an offset X-ray halo (Hayakawa *et al.* 2004) and a region of high velocity dispersion in the halo light (Hilker *et al.*, in prep.). Taken all together, this points to a non-equilibrium situation in the core of Hydra I. The central galaxy seems not to be at rest with the cluster potential well, and infalling substructure is building up the central halo and intra-cluster light. Thus we are witnessing ‘ongoing formation’ of a central cluster halo.



**Figure 2.** *Left panels:* GCs around NGC 3311 in Hydra I in the  $(U - V)$ - $(V - I)$  color-color space. Single stellar population tracks from PARSEC models (Bressan *et al.* 2012) for various ages (dashed lines) and metallicities (solid lines) are overlaid. In the upper panel, the region of old GCs (dark grey dots) is highlighted by a blue ellipse, in the lower panel the region for young ( $< 2$  Gyr) GCs. *Right panels:* spatial distribution of the selected old, metal-poor GCs (upper panel) and the young GCs (lower panel). White ellipses indicate the central major galaxies in Hydra I. The scale on the right are numbers per square arcmin. Note that the comparison background field is located several degrees east of the cluster.

#### 4. The most massive GCs=UCDs: two formation channels

As mentioned in the introduction, very massive GCs cannot easily be distinguished from so-called ultra-compact dwarf galaxies (UCDs). One should rather think of the different formation channels that can lead to rather compact ( $r_{\text{eff}} = 3\text{-}100$  pc) objects in the mass range  $10^6 < M < 10^8 M_{\odot}$ . One viable channel is the disruption of nucleated (dwarf) galaxies on radial orbits that pass the central cluster galaxies at small perigalactic radii and leave a 'naked' UCD-like stripped nucleus behind. However, cosmological simulations combined with a semi-analytic description to identify disrupted satellite galaxies suggest that this only explains the observed number of UCDs more massive than  $M > 10^{7.3} M_{\odot}$  (Pfeffer *et al.* 2014). The observed number of lower mass UCDs is much larger than that of predicted stripped nuclei. They should, thus, be of star cluster origin, either formed as very massive genuine globular cluster (e.g., Murray 2009) or being the result of merged star cluster complexes (Fellhauer & Kroupa 2002).



**Figure 3.** Left: UCD in the Fornax cluster that shows prominent tidal tail-like structures that extend out to 350 pc. The arrow indicates the direction towards the central Fornax galaxy NGC 1399. Right: Remote UCD (blue circle) at 85 kpc distance to NGC 1399 that harbours four GC candidates (green circles) within 1 kpc (red circle). The objects are labeled with their Washington  $C - T_1$  colors (from Dirsch *et al.* 2003). The figures are taken from Voggel, Hilker & Richtler (2016).

In order to constrain the formation of UCDs we have studied the structural composition and clustering properties of 97 UCDs in the halo of NGC 1399, the central Fornax galaxy (see contribution by Voggel, Hilker & Richtler, this volume). We found evidence for faint stellar envelopes around several UCDs with effective radii of up to 90 pc. One particularly extended UCD shows clear signs of tidal tails extending out to  $\sim 350$  pc (see Fig. 3, left panel). This is the first time that a tidal tail has been detected around a UCD. But the most striking result is that we detect, in a statistical sense, a local overdensity of GCs on scales of  $\leq 1$  kpc around UCDs. In particular blue (likely metal-poor) GCs are clustered around UCDs. These could either be remnant GCs of a formerly rich GCS around a disrupted nucleated dwarf galaxy, or surviving star clusters of a merged super star cluster complex (e.g., Brüns *et al.* 2009). A remote UCD, 85 kpc south of NGC 1399, possesses four GC candidates within 1 kpc radius, well within its tidal radius of 1.36 kpc, but shows no signs of a faint envelope in the same radius (see Fig. 3). The nature of this configuration is intriguing, pointing to a progenitor object that had a very rich substructure, maybe a complex star cluster system formed in- or outside a former host galaxy. Radial velocity measurements have to show whether the companion GCs are indeed bound to the host UCD.

## 5. Summary and outlook

Our general conclusions from the findings in the Fornax and Hydra I galaxy clusters shown in this contribution can be summarized as follows:

- In general, old globular clusters are good tracers of spheroid (red GCs) and halo (blue GCs) populations of ellipticals.
- The predominant GC population in the outer halo regions are the blue GCs. They trace the halo assembly history.
- Kinematics together with metal abundances of GCs is a powerful tool to find substructures and trace recent accretion events.
- In an appropriate 3-color space, sub-populations of blue GCs can be identified. Blue is not the same as *blue!*

- Ultra-compact dwarf galaxies (=the most massive star clusters) are a mixed bag of objects: most of them (>80%) are of star cluster origin.
- Extended stellar envelopes and overdensities of star clusters around them might hint to the accretion of nucleated dwarf galaxies or evolved super star cluster complexes.

In the coming years we will see great progress in extra-galactic globular cluster science. The Virgo and Fornax clusters are being scrutinized by photometric multi-wavelength wide-field surveys, covering the *U*- to the *K*-band. GCs and UCDs serve as one of the main tracers of the spatial distribution of baryonic structure in these clusters. Massive spectroscopic follow-up surveys are or will be launched to collect radial velocities and element abundances of thousands of GCs and UCDs around the central cluster galaxies in order to find chemo-dynamical substructures that constrain their halo assembly history.

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