1 Introduction

The realm of dwarf galaxies was extensively studied only in the last three decades. Dwarf spheroidals are considered to be the faintest galaxies, having baryonic masses comparable to those of bright globular clusters ($\sim 10^5 M_\odot$), but being 50-200 times more extended. Thus far one thought that dwarf galaxies were diffuse structures, with the exception of the compact elliptical M32 which is $\sim$8-10 times smaller than dwarf ellipticals of comparable luminosities but about 150 times more luminous than the brightest globular clusters of the Local Group. This gap in luminosity of compact stellar systems started to be filled in observationally during the last decade thanks to several large spectroscopic surveys in nearby galaxy clusters. The question arises what are the physical parameters and what is the origin of objects in the transition region between dwarf galaxies and star clusters? What is the smallest compact galaxy? What is the largest globular cluster? How can a massive cluster be discerned from a low-mass compact galaxy?

2 The discovery of compact objects

2.1 Celebrating the 10-years anniversary of “UCDs”

The discovery history of very massive compact star clusters started about 10 years ago. In a small spectroscopic survey of the globular cluster system of NGC 1399, the central galaxy of the Fornax cluster, Minniti et al. [1] confirmed a bright compact object as radial velocity member of the cluster: ‘... Note that the objects at $V = 18.5$, $V - I = 1.48$ (our reddest “globular cluster”), which has $M_V = -12.5$, was identified as a compact dwarf galaxy on the images after light-profile analysis (M. Hilker, 1996, private communication [2]) ...”. In another spectroscopic survey, designed as a follow-up of a photometric investigation of the surface brightness-magnitude relation of dwarf ellipticals in the Fornax cluster, Hilker et al. [3] confirmed in 1999 two bright compact objects (including the one mentioned before) as Fornax members. They proposed that they ‘... can be explained by a very bright GC as well as by a compact elliptical like M32. Another explanation might be that
these objects represent the nuclei of dissolved dE,Ns...’. Further they sug-
gested that ‘... It would be interesting to investigate, whether there are more
objects of this kind hidden among the high surface brightness objects in the
central Fornax cluster...’.

Indeed, only one year later, in 2000, a systematic all-object spectroscopic
survey within in a 2-degree field centred on the Fornax cluster revealed five
compact Fornax members in the magnitude range $-13.5 < M_V < -12.0$ [4]
which later, in 2001, were dubbed “Ultracompact Dwarf Galaxies” (UCDs)
by Phillipps et al. [5]. Their physical properties were presented in a Nature
article by Drinkwater et al. in 2003 [6].

2.2 A word on nomenclature

Before the term “ultracompact dwarf galaxy” (UCD) was invented, the new
type of objects was circumscribed in different ways: e.g. compact stellar ob-
ject, compact object, compact stellar system, (extremely) compact dwarf
galaxy, super-massive star cluster, extremely large star cluster, etc.

After its introduction, the denomination “ultracompact dwarf galaxy”
became widely used, but also provoked severe criticism, since it suggests that
these objects have a galaxian origin. The term “ultra-diffuse star cluster”
was opposed by Kissler-Patig [7] to demonstrate their link to massive star
cluster formation. In an attempt to find a neutral description Haşegan et
al. [8] named newly discovered compact objects in the Virgo cluster “dwarf-
globular transition objects” (DGTOs).

One should note that star clusters of similar luminosities and sizes as
UCDs/DGTOs are known in present-day galaxies, like the nuclear (star) clusters
(NCs) of late-type spirals and dwarf ellipticals and the super-star clusters
(SSCs) or young massive clusters (YMCs) of merger/starburst galaxies.

In this contribution, I will stay for simplicity with the term UCD to
describe objects with properties as summarized in the next section. Note
however that I don’t suggest that they are of galaxian origin. In contrary, I
will argue that they may be an inhomogeneous group of objects perhaps with
different origins.

2.3 UCD properties

Once the existence of UCDs in the Fornax and Virgo clusters was proven
by radial velocity measurements, e.g. [3],[4],[8],[9], their physical parameters
became the subject of much study. In particular, their sizes, shapes, metallici-
ties, ages, internal kinematics, masses and mass-to-light ratios are of interest.
Recent and ongoing observing programmes, employing high-resolution imag-
ing (HST) and spectroscopy (VLT and Keck) as well as high signal-to-noise
spectroscopy and deep imaging to faint surface brightnesses, revealed most of
those parameters for Fornax and Virgo UCDs [6],[8],[10],[11],[12]. The general
properties are listed in Table 1.
### Table 1. General properties of UCDs (LSB = low surface brightness).

| Property                        | Value                                                                 |
|---------------------------------|----------------------------------------------------------------------|
| Luminosity                      | $-13.5 < M_V < -11.5$ mag                                           |
| Colour                          | Fornax: mainly red; Virgo: mainly blue                              |
| LSB features                    | some have LSB envelopes with $80 < R_{eff} < 120$ pc                |
| Shape                           | best represented by King+Sérsic or Nuker profile                    |
| Effective radius                | $10 < R_{eff} < 30$ pc                                             |
| Velocity dispersion             | $25 < \sigma_0 < 45$ km s$^{-1}$ (central value)                    |
| Mass                            | $M = 2.9 \times 10^7 M_\odot$                                      |
| Mass-to-light ratio             | $M/L_V = 2.5$; Virgo DGTOs: $2.9$ (global value)                    |
| Metallicity                     | Fornax: $-0.5$ dex; Virgo: $-1.2$ dex, $[\alpha/Fe] = 0.3$          |
| Age                             | old: $>8$-10 Gyr                                                   |

### 3 “The UCD Rush”

After the first discovery of UCDs in the Fornax cluster, many surveys followed to search for UCDs in different environments and towards fainter magnitudes.

In the Fornax cluster, Mieske et al. [13] identified compact objects in the brightness range $-12.0 < M_V < -10.0$ mag. They found that their distribution over luminosity is consistent with an extrapolation of the GC luminosity function. Jones et al. [9] discovered a sixth bright UCD in the central two degrees of the cluster, but could not find any UCD brighter than $M_V = -12.0$ in an all-object spectroscopic survey of two adjacent 2-degree fields. The spatial distribution of GCs and UCDs in Fornax shows that UCDs brighter than $M_V \approx -11.5$ do not seem to belong to certain galaxies, but rather live in the intra-cluster space of the core region of the cluster.

In the Virgo cluster, Haşegan et al. [8] identified close to the central galaxy M87 six DGTOs and 13 DGTO candidates in the magnitude range $-11.8 < M_V < -10.8$. Three of the DGTOs have global $M/L_V$ of the order 6-9 that cannot be explained by stellar population models. Jones et al. [9] discovered 9 UCDs with $-13.7 < M_V < -11.5$ in a 2-degree field around M87, widely distributed throughout intra-cluster space.

In other surveys, nearby groups and distant massive clusters were searched for UCDs. Around Centaurus A several bright GCs with $M_V > -11.2$ were identified, e.g. [14], but no massive UCDs. Those seem also to be absent in other nearby groups. In the very massive lensing cluster Abell 1689, two twins of M32 were discovered and several massive UCD candidates [15].

### 4 Filling the parameter space of hot stellar systems

The physical parameters of UCDs have been compared to those of bright star clusters (young and old) and galactic nuclei by many authors. It is of special
Fig. 1. Luminosity-size relation for GCs, UCDs, compact ellipticals and dwarf elliptical nuclei as indicated in the plot (data taken from the literature). The diagonal dashed lines are lines of constant surface intensity. The horizontal dotted line shows the average effective radius of “normal” GCs in the Fornax cluster, \( \langle r_{\text{eff}} \rangle = 2.7 \) pc.

interest whether UCDs lie on known scaling relations in the parameter space of hot stellar systems. The most commonly used parameters for comparison are the absolute magnitude or mass (if available), the central or effective surface brightness, the effective (= half-light) radius, the central velocity dispersion, or combinations of such parameters (e.g. \( \kappa \)-space).

Here, the luminosity-size and luminosity-velocity dispersion plane, as well as a colour magnitude diagram of Fornax and Virgo UCDs are presented.

Fig. 1 shows that Galactic GCs with \( M_V < -7.5 \) and GCs in the Fornax cluster (dotted line) scatter around a luminosity-independent size of about 2.7 parsec. Objects brighter than \( M_V \simeq -10.5 \), however, follow a luminosity-size relation, approximately along a line of constant surface density. M32-type galaxies lie on the extension of this relation. Also nuclei of early-type galaxies exhibit a luminosity-size relation, shifted towards smaller sizes at a given luminosity. Note that young massive star clusters in starburst/merger galaxies follow a mass-size relation that is consistent with that of UCDs \[16\].
Concerning their internal kinematical properties, compact objects brighter than $M_V \simeq -10.5$ also seem to deviate from the well defined relation of “normal” GCs (see Fig. 2). In the luminosity-velocity dispersion diagram, UCDs seem to bend over towards the Faber-Jackson relation of early-type galaxies.

The colour magnitude diagram in Fig. 3 exhibits some interesting differences between Fornax and Virgo UCDs. In the magnitude range $-13.0 < M_V < -11.5$, the Fornax UCDs are dominantly red ([Fe/H] $\simeq -0.5$), whereas the colour of most Virgo UCDs is blue ([Fe/H] $\simeq -1.2$) and consistent with that of dE nuclei. Note that the two brightest UCDs are at least twice as luminous as the second brightest UCD in their respective clusters. Both are metal-rich and possess a small envelope of low surface brightness.

5 Formation scenarios for UCDs

Various formation scenarios have been suggested to explain the origin of UCDs. The three most promising and their implications are:
1) UCDs are the remnant nuclei of galaxies that have been significantly stripped in the cluster environment, also referred to as the “threshing scenario”, e.g. [17], [18]. Numerical simulations have shown that nucleated dEs can be disrupted in a galaxy cluster potential under specific conditions and that the remnant nuclei resemble UCDs in their structural parameters [18]. Good candidates for isolated nuclei are the Galactic globular clusters ω Centauri [21] and M54 as the nucleus of the Sagittarius dSph.

In Fornax and Virgo, the present-day nuclei of dwarf ellipticals are less massive and more compact than the UCDs. This implies that the progenitor galaxies must have been very massive dE,Ns or maybe late-type spirals. The small number of UCDs in both clusters points to a rather selective “threshing” process. The high metallicity of the Fornax UCDs seems to disfavour this scenario for their origin.

2) UCDs have formed from the agglomeration of many young, massive star clusters that were created during merger events, e.g. [19], [20], [16]. Inspired by the massive star forming knots in the Antennae galaxies, Kroupa [19] first showed that the individual star clusters in complexes can merge to form a
large massive, single star cluster. This work thus constitutes a prediction of UCD-type objects made right at the time when these were discovered. An evolved example of such a merged star cluster complex might be the 300 Myr old, super-star cluster W3 in NGC 7252 [22,23].

If the old UCDs in Fornax and Virgo formed like this, the galaxy mergers must have happened early in the galaxy cluster formation history when the merging galaxies were still gas-rich. However, in the case of Fornax, these early mergers must have already possessed close to solar metallicity gas. The small number of UCDs would imply that only the most massive star cluster complexes survived as bound systems.

3) UCDs are the brightest globular clusters and were formed in the same GC formation event as their less massive counterparts, e.g. [13,14]. The smooth shape of the bright end of the GC luminosity function (no excess objects!) might support this scenario.

The most massive GCs then supposedly formed from the most massive molecular clouds (MCs) of their host galaxy, where more massive galaxies were able to form higher mass MCs (as e.g. M87) than lower mass galaxies (as e.g. M31). The luminosity-size relation of the most massive clusters suggests that there is a break of the formation/collapse physics at a critical MC mass. In Fornax, the formation of the most massive GCs was connected to that of the metal-rich bulge GCs, whereas in Virgo they must have formed with the metal-poor GCs, if this scenario would be correct.

In an attempt to unify the ideas of the different formation scenarios one might think of the following generalized scheme of massive star cluster formation: GCs with a mass of \( \leq 5 \times 10^6 M_\odot \) are “single-collapse” GCs (SCGCs), i.e. their stars share a single age and metallicity. At a critical mass of \( \approx 5 \times 10^6 M_\odot \) the formation physics changes to “multiple-collapse” GCs (MCGCs) because the giant MC fragments into massive clusters as it contracts. The growth of SCGCs to MCGCs through merging can happen on different time scales. An immediate growth \((\sim 10-100 \text{ Myr})\) would correspond to the situation in super-star cluster complexes in mergers. The stars formed in the resulting MCGC then would have the same age and probably similar metallicities, although MCGCs would also be able to capture a substantial amount of older field stars from the host galaxy [19]. A successive growth over gigayears reflects the situation in nuclear star clusters. Nuclei of dwarf ellipticals could have formed via the merging of GCs which not necessarily had all the same age and/or metallicity. Another way of growing a nuclear star cluster is via episodic star formation of infalling gas in the centre of a gas-rich galaxy. The stars of those MCGCs are supposed to show a spread in ages and metallicities. Finally, through whichever channel the MCGCs formed, their evolution in the tidal field of a dense galaxy cluster over a Hubble time could have given rise to the population of old, isolated, massive, compact stellar systems we nowadays call UCDs.
6 Summary and Outlook

The name “ultracompact dwarf galaxies” (UCDs) collects/paraphrases old stellar systems in the transition region of globular clusters and compact dwarf galaxies ($-13.5 < M_V < -11.5$, $2.9 \times 10^7 M_\odot$, $10 < r_h < 30$ pc, $25 < \sigma_0 < 45$ km s$^{-1}$). The known UCDs are found in the cores of galaxy clusters and are not concentrated towards individual galaxies unlike most of the GCs.

While we have good ideas on their possible origin, there are many questions left to answer concerning the nature of UCDs. Some important ones are: Do UCDs have multiple stellar populations? Why do some UCDs have high M/L ratios? Is this due to tides? Or do they contain dark matter? Is there tidal structure around UCDs? Do UCDs harbour black holes? What are the kinematics of UCDs within their host clusters?

Some of these questions will be answered in the next years with the help of ongoing and future observing programmes. The results will bring more light into the nature of these enigmatic objects.

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