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A comprehensive study of the color distributions of dwarf early-type galaxies

Hamraz, Elaheh

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A comprehensive study of the color distributions of dwarf early-type galaxies

PhD thesis

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and in accordance with
the decision by the College of Deans.

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by

Elaheh Hamraz

born on 1 April 1987
in Zanjan, Iran

Supervisors

Prof. R. F. Peletier

Prof. H. G. Khosroshahi

Prof. E. A. Valentijn

Assessment Committee

Prof. S. C. Trager

Prof. H. Salo

Prof. M. Baes

Front cover: Color (u-g) image of FCC282, a dwarf early-type galaxy in the Fornax cluster presented in chapter 4 of this thesis. Substructures are distinguishable in this image. This galaxy is detected in CO as well.

Back cover: The Fornax Galaxy Cluster by VLT Survey Telescope. Credit: ESO.

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1

Introduction

Dwarf galaxies are the most abundant galaxies in the Universe. Since they are faint and small in size, they have not been studied as much as other types of galaxies. In this study, we will investigate the physics of dwarf early-type galaxies by studying their colors, as a proxy of their stellar populations, and their scaling relations. We will also explore how the environment of these galaxies influences their properties. To better understand this study, one needs to know galaxy classification, the definition of dwarfs, what their most important parameters are, how the environment acts on them, and the need of high quality/resolution imaging for these studies. We start with an introduction, at beginners' level, and gradually introduce more and more concepts.

1.1 Galaxies and their morphology

From an historical point of view, the general opinion was that the Milky Way galaxy is the entire Universe. Edwin Hubble claimed that the Andromeda nebula, a faint, fuzzy nebula in the sky, is not a part of our Milky Way galaxy. Using the distance of individual, variable stars in such nebulae, he showed that there were indeed objects that were situated at large distances from our own Milky Way (Hubble 1929). Today we know that galaxies are gravitationally bound systems composed of stars, interstellar material, such as gas and dust, and an unobserved component called dark matter to account for the missing mass. Although telescopes and astronomical instruments using the newest technology have made a huge difference in our understanding of galaxies, there are still many questions about galaxies that remain unanswered: How and when did they form? What are the important factors that determine the morphology of a galaxy? How do they interact with their environments? Do

Figure 1.1 – Hubble tuning fork; Hubble classification of nebulae (Hubble 1929).

they have dark matter? If they do, how is the dark matter distributed? And more similar questions which astronomers are investigating to find an answer (Jones, Lambourne & Serjeant 2015).

Since galaxies are found in a variety of shapes, it is important to classify them in order to understand their evolution. From a historical point of view, the easiest way to classify the galaxies is by their morphology at the optical wavelengths. The main galaxy classification system which is still being used today was introduced and developed by Hubble (1926). This scheme is called the Hubble classification or "Hubble Tuning Fork", shown in Figure 1.1. The basic Hubble sequence consists of two main branches of galaxies: ellipticals and spirals (also called as early-types and late-types), based on whether they have spiral arms or not. A further classification of spirals divides them into two sub-groups: with (SB) and without bars (S). The elliptical sequence is determined by the overall shape of the galaxy, E_n , where n is an indication of the ellipticity, $n = 10(1 - b/a)$. In this formula, a and b are the major and minor axes. Accordingly, an elliptical with a round appearance is indicated by E_0 while E_7 refers to a highly elongated elliptical. The spiral class is divided into three types; S_a , S_b and S_c , depending on the bulge to disk brightness ratio and how wound-up and smooth the spiral arms are. There is a fraction of galaxies which does not look either spiral or elliptical and do not typically have distinguishable structures. These galaxies are known to be in the interaction phase or are dwarf galaxies.

Later, in 1936, Hubble added a new class of galaxies to his tuning fork, called

Figure 1.2 – Updated version of the Hubble classification by Kormendy & Bender (1996), with an added class of irregular galaxies, and a revised early-type class with disk and boxy shapes.

Lenticulars (S0), which is an intermediate class between ellipticals and spirals. These galaxies have much higher bulge-to-disc ratios than typical spirals, although they do not have any dominant spiral arms. Over the years the Hubble classification has been revised and some features like bars, rings, irregular galaxies and dwarf ellipticals have been added. An example of a modern form of the Hubble sequence is the classification made by Kormendy & Bender (1996), Figure 1.2. This extension of the Hubble sequence contains the disk and boxy character of ellipticals. Also, the class of irregulars was added. The whole history of Hubble’s tuning fork and more recent visual classification details can be found in Buta (2013).

1.2 Galaxies and their photometry

Photometry is an important part of observational astronomy. It is the science of measuring the flux which is received from celestial objects. This way you can measure the brightness of objects, and the relative distance compared to objects of the same type. By measuring the flux of an object in two different bands, a color can be calculated as well. The color of an object contains information about its physical nature, such as temperature, stellar content, etc.

For spatially extended objects such as galaxies, it is also important to measure the spatial distribution of the surface brightness within the galaxy rather than simply measuring its total brightness. This results in a surface brightness profile of a galaxy, which is measured as a function of the distance from the center of the galaxy. This profile provides information about the internal structure

of the object. Another important parameter is the radial color profile which gives us information on how the stellar populations change radially.

The isophotes of elliptical galaxies are mostly fitted by ellipses. Each ellipse can be characterized by two parameters: its minor-to-major axis ratio b/a (or, equivalently, by their ellipticity $\varepsilon = 1 - b/a$) and position angle of the major axis. Normally, ellipticity and position angle do not change very much as a function of radius, unless the galaxy is distorted. Change of position angle with radius is called isophote twisting. It is assumed that twists can be caused by tidal interactions. Furthermore, their occurrence correlates strongly with the presence of companions. Sometimes position angle twists are shown in isolated galaxies. In such galaxies they are evidence that these objects are triaxial.

de Vaucouleurs (1948) was the first one who measured the light distribution of ellipticals in various apertures and proposed a fitting form (Mo, van den Bosch & White 2010). de Vaucouleurs defined the $r^{1/4}$ law, which fitted elliptical galaxies very well. Today, the general model to describe ellipticals and dwarfs is the Sérsic law (Sérsic 1963) shown by the formula below:

$$I(r) = I_0 \exp(-(r/a)^{1/n}) \quad (1.1)$$

Here I_0 is the intensity at the center, 'a' is the scale length (radius at which intensity drops by e^{-1}) and 'n' is the Sérsic index which is a shape parameter. Varying the Sérsic index results in various profiles as can be found in Figure 1.3. $n=0.5$, 1 and 4 make Gaussian, Exponential and de Vaucouleurs profiles, respectively. The Sérsic indices of ellipticals are found to be between 1.5 and 10. On top of that, ellipticals often have central cores. The core-Sérsic model is an advanced Sérsic model to describe galaxies with cores.

1.3 Dwarf Galaxies

Dwarfs are the most abundant galaxies in the Universe, whereas they contain a relatively small fraction of all stars. Since the first dwarf elliptical (dE) galaxy was discovered after the second half of the 20th century, they were not included in the original Hubble classification. According to the classic definition, dEs are low luminosity galaxies at the faint end of the sequence of the ellipticals, $M_B > -18$ (Sandage & Binggeli 1984), with smooth surface brightness profiles. Sandage & Binggeli (1984) classified early-type dwarf galaxies as dS0s and dEs depending on whether the galaxy contained a disk component in the center of their smooth spherical appearance or not. Their version of the classification diagram for dwarfs is shown in Figure 1.4.

As a result of the continuous increase in the size of telescopes and the sensitivity of the advanced detectors, also due to the improved observational facilities,

Figure 1.3 – This image shows different surface brightness profile with varying Sérsic index (n). $n=1$ returns an Exponential profile, $n=0.5$ is a Gaussian and $n=4$ makes a de Vaucouleurs profile.

more details of dwarf ellipticals were observed, leading to changes in our picture of their formation and evolution. The first impression from decades ago, that dwarf galaxies possess simple structures, has changed totally in the sense that a classical morphological division of them is meaningless in view of the variety of the dwarf galaxy types: dwarf elliptical galaxies (dEs), dwarf irregular galaxies (dIrrs) and dwarf spheroidals (dSphs). There are also some other new kinds of dwarf galaxies that have recently been discovered: very low surface brightness, ultrafaint dwarfs (uFd), centrally concentrated actively star-forming BCDs and Ultra Diffuse Galaxies (UDGs). The new class of ultracompact dwarfs (UCDs) consists of galaxies which are as compact as Globular Clusters (Tolstoy, Hill & Tosi 2009). Most of the dwarfs in clusters are dE or dSph, whereas dIrrs are mostly located in the field. Figure 1.5 shows half-light radius versus luminosity for most of these classified types.

Many studies have addressed the question whether dEs are the low surface-brightness extension of giant ellipticals or whether they belong to another class, as they follow different properties (e.g. Sandage & Binggeli 1984; Lisker & Han 2008; Kormendy 2009). The surface brightness of classical elliptical galaxies approximately follows a Sérsic profile with $n > 2.5$, whereas the surface brightness profile of dEs is more close to an exponential (Graham & Guzmán

Figure 1.4 – The classification system of the Sandage & Binggeli (1984) Atlas which shows the different morphological types in the luminosity- morphological type plot. The circles represent the major classes. Dotted lines indicate a possible connection. The numbers beside each circle represent panel number of their illustrations, (to see more check, Sandage & Binggeli 1984)

2003). Note that spiral disks also have exponential profiles, which relates dEs to disks in a way.

By focusing on the structural properties of dEs versus classical giant ellipticals, the discontinuity is seen easily in photometric diagrams such as the one shown by Graham & Guzmán (2003), Figure 1.6. It is shown that, below a certain mass, the so-called dwarfs separate from their more massive family in structural properties such as surface brightness and effective radius. These differences are used to interpret that different physical processes are important for their evolution and that the properties of these two classes correspond to two different formation processes. Although it is still a matter of debate what these formation mechanisms are.

In one of the most cited papers on the difference between giants and dwarfs, Kormendy (1985) claimed that there is a strong dichotomy at $M_B \sim -18$, between giant and dwarf ellipticals as seen in their surface brightness- magnitude diagram, which he explained as a result of different formation processes. Despite these results of Kormendy, Graham & Guzmán (2003) used the result of Figure 1.6 and reported that by having a more complete sample around

Figure 1.5 – *Luminosity- half-light radius diagram from Brodie et al. (2011). It includes Globular clusters (GCs), ultracompact dwarfs (UCDs), extended clusters (ECs), dwarf spheroidals (dSphs), Dwarf elliptical galaxies (dEs), ultrafaint dSphs, giant ellipticals (gEs), and compact ellipticals (cEs).*

$M_B \sim -18 \pm 1$, the two groups are connected and dwarfs and giants together form one sequence. Graham & Guzmán (2003) explained the difference in slopes using a core formation mechanism that changes the central brightness of the luminous galaxies (For more discussion see Graham & Guzmán 2003).

1.4 Color and the color-magnitude diagram

Color of a galaxy is one of the properties that can be used to classify them. It is defined as the difference between the magnitudes of two filters. Normally early- and late-type galaxies can be distinguish by their red and blue colors respectively. Compared to morphology type, colors are easier to measure, especially for very small galaxies.

Figure 1.6 – Photometric diagrams showing the dichotomy between ellipticals and dEs from Graham & Guzmán (2003). The y-axes show B-band magnitude, Sérsic index and effective radius. The x-axes show average surface brightness within the effective radius, surface brightness at the effective radius and central surface brightness. Dots, triangles, and five-pointed stars represent dE galaxies whereas asterisks, open circles and filled circles represent elliptical galaxies in various samples from the mentioned authors in their paper.

Figure 1.7 – Color, luminosity and temperature of stars in their life time. The main sequence is where stars spend most of their life time.

Stars are the main baryonic content of galaxies, therefore the light coming from a galaxy and its color mainly contains information about its stars. To understand the evolution of a galaxy, one can study the evolution of its stars. Basically, the color of the light that a star emits is related to its temperature in a way that hotter stars are bluer and the cooler the star the redder it is. Stars can be found on the main sequence for most of their life time, which means that they burn Hydrogen in a nuclear reaction to make the energy to overcome their collapse due to their own gravitation. As a star runs out of Hydrogen, its size and temperature changes. At this time it becomes cooler, larger and red. This explains why older stars are redder than young ones. Figure 1.7 shows a simple scheme of color, luminosity and temperature of stars in their life time. As is seen in this figure, stars change their colors from blue to red as they become older. A galaxy with a large number of young stars will appear blue like spiral galaxies, which normally have active star formation, whereas elliptical galaxies normally are red.

The color-magnitude diagram (CMD) of galaxies is an important parameter that shows the relation between their absolute magnitude as an indicator of

Figure 1.8 – An example of color-magnitude diagram from Gavazzi et al. (2010). The red dots are early-type galaxies (dE-E-S0-S0a), the blue dots are disk galaxies (Sbc-Im-BCD) and the greens are bulge galaxies (Sa-Sb). Lower panels show late-types in the left and early-types in the right. The solid line represents the empirical separation between the red-sequence and the remaining galaxies.

mass and their color, as an indication of their stellar populations. Plotting a CMD, a bi-modal distribution of galaxies can be identified: an area with high luminosity and red galaxies and the other with faint magnitudes and blue color. The slope of the fitted line to the first red area is called the 'red sequence' and the blue area is called the 'blue cloud'. A less populated area in the middle is called 'green valley' (Baldry et al. 2004). Unlike the comparable Hertzsprung–Russell diagram, which is the CMD of stars, galaxies properties are not necessarily completely determined by their location on their CMD. An example of a color-magnitude of galaxies can be found in papers like Gavazzi et al. (2010) who used a rich sample of galaxies from SDSS containing many clusters, groups and many filamentary structures which is shown in Figure 1.8.

Early-type galaxies which are the galaxies studied in this work, have red colors in general indicating that they are dominated by the old, metal-rich stars. This is not for dwarfs, where the metallicity is fairly low. There is a correlation between their luminosity and color in a way that brighter ellipticals are redder (Sandage & Visvanathan 1978).

1.5 Galaxies and their environments

Although the whole process of galaxy formation and evolution is not well understood yet, there are many theories about their origins and evolution. White & Rees (1978) were the first ones who suggested a hierarchy formation for galaxies. In their scenario the smaller galaxies which have formed, join together to make more massive ones. In order to explain how the first galaxies formed, we should refer to Λ CDM cosmology, which is the most popular cosmological model (for a comprehensive review of this model see Mo, van den Bosch & White (2010)). In this cosmological model, the first structures in the early universe formed through small density fluctuations making dark matter halos, which are the base of the galaxies that we see today. The baryonic matter then sinks into these halos and clumps together to make the first stars and so the first proto-galaxies. This is a very simplified model of galaxy formation. For more details see Mo, van den Bosch & White (2010).

Galaxies are not found in isolation, but generally in groups or clusters. The smallest aggregation of galaxies is called a group, which is the most common structure of galaxies in the universe. Typical groups contain between three and fifty members with a radius in the range 0.1 to $1 h^{-1} Mpc$ (Mo, van den Bosch & White 2010). Groups have a mass ranging between those of very large elliptical galaxies and mass of clusters (Muñoz et al. 2013). The total mass of the group is typically $\sim 10^{13}$ solar masses, and the velocity dispersion is about $150 km/s$. The mass to light ratio found in groups of galaxies is about $100h (M_{\odot}/L_{\odot})$, indicating the presence of large amounts of non-luminous matter or dark matter

(Mo, van den Bosch & White 2010).

Galaxy clusters are the environment which we will investigate more in this thesis. They are larger than groups, although there is not any sharp dividing line between them. The typical mass of clusters is about $10^{15} M_{\odot}$, and a typical volumes is about $100 Mpc^3$. Around 80% of the cluster mass consists of dark matter, 3–5% is in form of luminous matter and the rest, which is about 15–17% is in diffuse hot gas form (Feretti et al. 2012). Richness and compactness can be used as two selection criteria to choose a cluster dynamically. According to these criteria, Abell (1958) selected 1682 galaxy clusters from the Palomar Sky Survey, which are now referred as the Abell clusters. These criteria is listed below:

- 1) Richness criterion: Each cluster must have at least 50 member galaxies with apparent magnitudes $m < m_3 + 2$, where m_3 is the apparent magnitude of the third brightest member. The richness of a cluster is defined as the number of member galaxies with apparent magnitudes between m_3 and $m_3 + 2$. Rich Abell clusters are those with richness greater than 50, although Abell also listed poor clusters with richness in the range between 30 and 50.
- 2) Compactness criterion: Only galaxies with distances to the cluster center smaller than $1.5 h^{-1} Mpc$ (Abell radius) are selected as members. Given the richness criterion, the compactness criterion is equivalent to a density criterion.

The third type of galaxy environment is the so-called field. A galaxy in the field does not belong to a gravitationally bound system such as a group or a cluster. The most common type of field galaxies is Sb although there are some field ellipticals. The galaxy content of field and clusters are different.

Studying the evolution of galaxies, the environment that a galaxy resides in, is one of the important factors to take into account. From the early studies when Hubble & Humason (1931) showed that the denser environments host a larger fraction of early-type galaxies, it is realized that the relative number density of each morphological type depends on their host environments. It is shown that the denser environments host galaxies that are on average more massive, redder, more concentrated, less gas-rich and have lower specific star-formation rates (Mo, van den Bosch & White 2010).

1.6 Formation and evolution of the dwarf early-types

The environment that a galaxy is located in, plays a very important role in its formation and evolution. Considering the shallow gravitational potential of dEs, they are more susceptible to internal and external mechanisms compared to more robust giant ellipticals. Various process happening in a group or a cluster, both galaxy-galaxy and galaxy-cluster interactions affect dEs more than

their more massive counterparts. The structure and morphology of a galaxy are two of the best ways to trace these processes (Conselice 2014; Dressler 1984; Postman et al. 2005). From the past to the present, there have been many theoretical and observational studies aiming to understand different environmental processes which play a role in the evolution of these galaxies, although many details of the formation and evolution of dEs are still unclear.

dEs are mostly located in high density galaxy environments (Binggeli, Tarenghi & Sandage 1990). Previous studies of dwarf early-types in clusters have opened a debate about the origin of these systems. Their seemingly simple and round appearance are the reasons to classify them as the low luminosity counterparts of massive elliptical galaxies, but there is no agreement yet on physical interpretation of the location of dwarf early-types on the scaling relations, whether they are the faint end of the brighter early-types or whether they are the remnants of bright late types with a star formation history quenched by the environmental effects. Quenching means turning off star formation and it simply happens when a galaxy runs out of the cold gas which stars are made from. The most important environmental effects related to dwarf galaxies are summarized below.

It was first Gunn & Gott (1972) who proposed that the Inter Stellar Medium (ISM) could be removed from galaxies moving at $\sim 1000 \text{ km s}^{-1}$ through the hot ($\sim 10^7 - 10^8 \text{ K}$) and dense ($\sim 10^{-3} - 10^{-4} \text{ atoms cm}^{-3}$) intergalactic medium by means of ram pressure mechanism. As individual galaxies move within such clusters, they experience this intra-cluster gas as a "wind". Ram pressure stripping occurs when this wind is strong enough to overcome the gravitational potential of the galaxy to remove the gas contained within it. During the ram pressure stripping process the galaxy which is in-falling into the cluster loses its gas and rapidly quenches its star formation. This process does not directly affect the stars and their angular momentum should be conserved. Ram pressure can effectively remove the ISM if it overcomes the gravitational pressure anchoring the gas to the disk:

$$\rho_{IGM} V_{gal}^2 \geq 2\pi G \Sigma_{star} \Sigma_{gas}, \quad (1.2)$$

where ρ_{IGM} is the density of the intergalactic medium, V_{gal} is the velocity of the galaxy inside the cluster, Σ_{star} is the star surface density, and Σ_{gas} is the gas surface density (Boselli & Gavazzi 2006).

Moore et al. (1996) proposed that the evolution of galaxies in clusters is governed by the combined effects of multiple high-speed galaxy-galaxy close ($\sim 50 \text{ kpc}$) encounters and the interaction with the potential of the cluster as a whole which is called "galaxy harassment". Harassment is a high-speed interaction between galaxies and depends on the collision frequency, the strength

of each collision, the cluster's tidal field, and the distribution of the potential within galaxies. Galaxy harassment is a significantly violent process that can remove a large fraction of the stellar mass, change the morphology of the galaxy, and lose a significant fraction of the angular momentum of the stars. It can also cause the gas to sink toward the center of the galaxy. Regarding the different potential distribution, the massive and dwarf galaxies react differently to the galaxy harassment. Dwarf galaxies are strongly perturbed by this interaction due to their low mass concentration and low surface brightness. They are expected to lose most (up to 50% – 90%) of their stars (Moore et al. 1999).

There are more types of gravitational interactions of galaxies such as galaxy-galaxy tidal interactions (Toomre & Toomre 1972), interactions with the cluster potential and galaxy mergers. The former occurs when the relative velocities and the relative distance of the galaxies are small. Galaxy-galaxy interactions are less effective in dense environments such as clusters compared to the field and groups.

1.7 Blue-cored star forming dwarf early-types

As discussed earlier, star formation is one of the important factors that determines the Hubble Classification of galaxies. It is a critical process as it leads to the formation of stars which galaxies do not exist without. It can change both the morphology and quantitative structure of the galaxy. Star forming galaxies which do not contain dust are blue with some star forming structures seen in their appearance. Normally, early-types are galaxies without any recent star formation activity although some studies have found some in dwarf ellipticals.

Early studies (e.g. Ferguson & Binggeli 1994) assumed that dEs are galaxies without any gas. However, by using better observational equipment, it was found that dEs are not always quiescent galaxies and they can host some spiral structure, recent or ongoing star formation, gas and dust content (Lisker et al. 2006; Grebel 2001; Jerjen, Kalnajs & Binggeli 2000; Hodge 1973). One of the first reports of finding a dE with star formation in its center outside the local group was Vigroux, Souviron & Vader (1984) as shown in Figure 1.9. In this Figure, the color profile of a galaxy with an extended blue center is shown. As it is shown this galaxy has a very blue central color.

The blue color of these cores can be explained by younger stellar populations in the center of these galaxies which is a result of star formation activity. The young stars are hot and massive with a blue color, while the old stellar populations in the main body of the galaxy are redder. The star forming activity is confirmed by the presence of $H\alpha$ emission and Balmer absorption

Figure 1.9 – Color profile of a galaxy with a blue center from Vigroux, Souviron & Vader (1984). East and west curves have been separated. The blue region extends up to 4 arcsec.

in some cases which are a strong probe of the star formation regions and new stars (Conselice et al. 2003; Gavazzi et al. 2003; Lisker et al. 2006).

A few Old studies reported finding these blue-core dwarfs in different environments. Peletier (1993) revealed a recent star forming region in the center of a dwarf elliptical: NGC205 (Messier 110). He presented the radial color profile in various colors and showed that the color profiles drop toward the center of the galaxy. Durrell (1997) reported a dE with a blue nucleus in the Virgo cluster.

More recently, taking advantage of high resolution data of telescopes such as the Hubble Space Telescope (HST) we can distinguish objects as small as nuclei of dwarf galaxies in nearby clusters (subarcsecond scales) much further than the local group. More discoveries of these blue cores have been published and caused a rise in their numbers. For instance, Lotz, Miller & Ferguson (2004) for a sample of dEs in the Leo Group, the Virgo and Fornax clusters, observed with HST WFPC2, showed that for dEs on average their nuclei are bluer than their underlying galaxies (for more studies on nucleus of dEs in the nearby

clusters see: Turner et al. 2012; Côté et al. 2006; Paudel, Lisker & Kuntschner 2011).

There are various possible formation mechanisms that can explain the star formation in the center of blue-cored dwarf early-types. Transition-type dwarf galaxies are examples of these formation scenarios. In this scenario, the environment of the galaxy with processes such as harassment and ram pressure stripping acts on an in-falling late-type galaxy and transforms it to a dwarf early-type. These processes can remove the ISM of the galaxy, quench the star formation, and in the meantime even re-ignite the star formation activity in the center of the galaxy. These galaxies can have properties of both early- and late-type galaxies (Boselli et al. 2008; Lisker et al. 2006; Kronberger et al. 2008). More details about these formation scenarios are given in Chapter 3.

1.8 Outline of this Thesis

As explained previously, the color of a galaxy contains important information about its evolution. The aim of this thesis is to expand our understanding of the physics of dEs by focusing on their colors by taking advantage of high resolution photometric images to not only study the outer parts of these galaxies, but also to zoom into the inner regions as small as a few parsec to investigate the center of dEs in nearby clusters as well. Calculating colors, we explore color-magnitude diagrams of dEs and investigate what information can be extracted from the position of a galaxy on the color-magnitude diagram. In addition, we use the color profile of each galaxy to find out how its color changes from the innermost part of a galaxy to its outer part. Beside color, we measure more photometric properties such as effective radius, magnitude, etc.

For this study we use a sample of dEs in the Fornax cluster. To examine how the environment can affect the color of a dE we compare our sample to similar ones in the Virgo and Coma clusters. The environmental differences between these clusters can guide us to find the effective processes responsible for the formation and evolution of these galaxies. Among the nearby clusters, Virgo is almost certainly the most studied. After Virgo with a distance of 16.5 Mpc, Fornax with a distance of 20 Mpc is the nearest and largest concentration of galaxies in the South (Blakeslee et al. 2009). The Fornax cluster is less massive, smaller and has a shallower potential well whereas Virgo is a very rich and active cluster with all kinds of galaxy-galaxy and galaxy-environment interactions such as ram-pressure stripping, tidal stirring, and galaxy harassment operating there. Comparing the cluster's environment, Coma is a relaxed, dense and rich cluster at a distance of 100 Mpc (Carter et al. 2008). The density of a galaxy's environment plays an important role in determining its star formation and quenching and from there in its color.

The major observations which are used in this study are the HST ACS surveys. The HST observation of these clusters are called the ACS Fornax Cluster Survey (ACSFCS), Virgo Cluster Survey (ACSVCS) and Coma Cluster Survey. The ACSVCS and ACSFCS Surveys targeted an unbiased sample of 143 early-type galaxies in the Virgo and Fornax clusters (100 in Virgo and 43 in Fornax). The images are available in HST Mikulski archive. For the Coma cluster, only a limited part of the cluster was observed, mostly in the central regions as the ACS camera failed during the later stage of the survey. We limited our samples to a specific magnitude range which is mostly refer to as the bright dEs.

In addition, to understand whether the blue star formation and dusty regions on the color maps of an dwarf early-type galaxy, can predict the presence of the molecular gas, we selected a sample of CO detected galaxies in the Fornax cluster and study their colors. CO is the most commonly observed tracer molecule of H_2 (Narayanan & Krumholz 2014). The galaxies with CO detection contain gas that can be used to form stars. To inspect their color maps and color profiles, the images of these galaxies in the Fornax Deep Survey (FDS) are used. The FDS is a new survey of the Fornax cluster which contains 573 galaxies in the optical bands using the ESO VLT Survey Telescope (VST). The imaging is done in the u, g, r and i-bands using the OmegaCAM instrument attached to the VST.

This thesis is organized as follows:

Chapter 2: In this chapter we aim to make a detailed study of the origin of the scatter in the color-magnitude relation of dEs in the nearby clusters. To do this, we use the photometric accuracy and stability of the HST images and choose a sample of archived HST imaging data. Therefore, we can study the origin of the scatter by comparing the clusters with each other, and by relating the position of a galaxy on the CMR with the features in its images, such as the presence of the dust, young stars, or galaxy truncation. The HST data-set is much better suited to do this with than any other currently in the literature. We discuss the CMR of three nearby clusters; Virgo, Fornax and Coma, in the magnitude range of $-18.7 \leq M_{g'} \leq -16.0$. We use the HST archive images and calculate the magnitudes, effective radii and colors of the dwarf early-types in Fornax cluster. To compare the color-magnitude diagram of the Fornax early-type dwarfs with the corresponding ones in Virgo and Coma, we benefit from already existing color measurements in the literature. We discuss the CMRs, their scatter, outliers and how they are related to the cluster environment.

Chapter 3: Following the first chapter, here we aim to determine the color gradient in the old populations (seen in the outer part) as well as the central

1 young populations. Since the cores of the galaxies contain information about the violent processes that have happened to the galaxies, studying them will shed light on our understanding of the formation and evolution of dwarf early-types. As den Brok et al. (2011) noticed, excluding the center of the early-type galaxies can influence the color gradient which is a key to distinguish stellar populations of the core. Distinguishing the core of a dwarf early-type in nearby clusters (as small as a few 10 pc), is rarely possible with the sharpest ground based telescopes (Grant, Kuipers & Phillipps 2005). The ground based telescopes can hardly resolve angles less than $1''$ which is about 100 pc at the distance of Fornax. The ACS camera on HST makes it possible to observe small nuclei with $R_e \sim 0''.025$ (Côté et al. 2006). With the advantage of the HST resolution and the sufficient separation of the F475W and F850LP HST bands to study the star formation, we can investigate more detailed color profiles of dwarf early-types in nearby clusters. To discuss the effects of cluster environment, similar to Chapter 2, we chose three clusters, with distinct characteristics, that have been studied by HST; Virgo, Fornax and Coma.

Chapter 4: Here we study the optical properties of a CO-detected (Zabel et al. 2019) sample in the Fornax cluster. We use the images of this sample from the Fornax Deep Survey (FDS) to investigate the color profiles and color images of these galaxies in the optical bands. Then we narrow our focus to the dwarf early-type galaxies of this sample and compare them to a control sample of dE galaxies, selected without information about their CO content. We will present the color profiles and color maps in the $g - r$ and $u - g$ as well as the residual maps of these galaxies, in order to discuss whether the presence of molecular gas is related to any features distinguishable in the optical.

A precise color-magnitude relation for bright early-type dwarfs in nearby clusters; a comparison between Fornax, Virgo and Coma

Elaheh Hamraz^{a, b}, Reynier F. Peletier^a, Habib G. Khosroshahi^b, Edwin A. Valentijn^a, Mark den Brok^c, Aku Venhola^{a, d}

^a Kapteyn Astronomical Institute, University of Groningen, Postbus 800, NL-9700 AV Groningen, the Netherlands

^b School of Astronomy, Institute for Research in Fundamental Sciences (IPM), Tehran, 19395-5746, Iran

^c Leibniz-Institut für Astrophysik Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany

^d Astronomy Research Unit, University of Oulu, Oulu, FI-90014 Finland

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Abstract

In an effort to study and understand the scatter of the color-magnitude relation (CMR) of early-type dwarf galaxies and its environmental dependence, we present color-magnitude relations for three nearby clusters: Fornax, Virgo and Coma. We use images from the Hubble Space Telescope (HST) of galaxies in the Fornax cluster in the magnitude range of $-18.7 \leq M_{g'} \leq -16.0$, and measure their magnitudes, effective radii and colors, and compare them with the HST literature measurements for Virgo and Coma. The photometric stability of HST allows us to have accurate color measurements and to understand the reason behind the scatter in the CMR. Comparing the CMRs of the three clusters, we find that the scatter in Virgo is considerably larger than in Fornax and the center of Coma cluster. The galaxies on the blue side of the CMR show blue light from young stars, attenuated by dust extinction, in the nuclei of the galaxies or more extended structures. Most of the outliers on the red side are compact early-type galaxies, with truncated surface brightness profiles and often companions of the large galaxies. Interestingly, no red outlying compact early-types are found in Fornax and Coma in this magnitude range while we find three in the Virgo cluster. We also find that the CMR of the Fornax and Virgo clusters are slightly bluer than that of Coma. We argue that the small scatter of the CMR, can be used as an effective tool to study the formation of galaxies and their stellar populations.

2.1 Introduction

Our understanding of galaxy formation and evolution is based on numerical models of the Universe. Parameters in these models are adjusted in order to reproduce a number of observations, such as the galaxy luminosity function, several scaling relations, the appearance of galaxies, the presence of AGNs and so on (for a review see Silk & Mamon 2012). One of the important scaling relations is the color–magnitude relation (CMR), connecting the magnitude of a galaxy, an indicator of its mass, to its color, an index of its stellar populations. This relation is fundamental, since it tightly connects a macroscopic property, galaxy mass, to small-scale quantities such as the constituting stellar populations. The CMR of the early-type galaxies is often called the ‘*red sequence*’, and is very pronounced in observations of galaxy clusters (e.g., Eisenhardt et al. 2007; Stott et al. 2009; Sánchez-Blázquez et al. 2014), and in large surveys such as Sloan Digital Sky Survey (SDSS) (e.g., Baldry et al. 2004).

Galaxies were positioned either on the red sequence or the blue cloud, a densely populated area in color–magnitude space where galaxies are found to show star formation. Between the red sequence and the blue cloud, one finds a relatively underpopulated region, called the green valley. The red sequence is known to built up over a relatively long period starting with the most massive galaxies. This process is called downsizing (Thomas et al. 2005; Choi et al. 2014). The red sequence has been identified in (proto) clusters up to $z=2$ (e.g., Muzzin et al. 2009; Taylor et al. 2009). Recently, there has been a considerable amount of work going on to understand the faint end of the red sequence, and to find out when dwarf galaxies end up on the red sequence (see Boselli & Gavazzi 2014; Boselli et al. 2014; Roediger et al. 2017; Schombert 2018, for an extended discussion about this).

To better understand the CMR, and therefore one of the influential aspects of galaxy formation, it is important to understand the origin of its scatter. Measuring the scatter is best done in galaxy clusters, since the distance errors are minimized, as all galaxies are roughly at the same distance. Bower, Lucey & Ellis (1992) measured a scatter in the relation between M_V and both $U - V$ and $V - K$ of ~ 0.05 – 0.06 mag for both the Virgo and Coma cluster, using a sample of giant ellipticals and S0 galaxies. For ellipticals only, the scatter reduces to ~ 0.03 – 0.04 mag by lowering the magnitude range to only 2 mag. For all cases the scatter is larger than the uncertainties in the data. Eisenhardt et al. (2007) found a similar result for the Coma cluster. There is therefore a consensus that the CMR of galaxies is tight, with nonzero intrinsic scatter that cannot be explained by observational uncertainties. It is generally accepted that this scatter is caused by young stellar populations, making the color bluer than expected for a given magnitude (Schweizer & Seitzer 1992). The CMR

and its scatter in a galaxy cluster are therefore a very useful tool to measure the evolutionary status of its galaxies.

It is generally known that dwarf galaxies have more extended star formation histories, and move to the red sequence only after their more massive counterparts (Downsizing, e.g., Thomas et al. 2005). For nearby clusters, where the red sequence is well in place for massive galaxies, dwarf galaxies are ideal to study their evolution. However, not many studies discuss the CMR in the mass range of dwarf galaxies, since they have low surface brightness, and wide-field imaging surveys have only recently become available. Janz & Lisker (2009) used SDSS data for early-types of the Virgo cluster and showed that the scatter around the CMR increases toward fainter magnitudes and that the scatter is intrinsic. Roediger et al. (2017) recently showed CMRs in optical colors for the galaxies in the center of the Virgo cluster. Their scatter is significantly lower than the one reported by Janz & Lisker (2009), and they also studied a considerably broader range of magnitudes. The fact that the precision of the magnitudes in both papers is similar for galaxies brighter than $M_g = -16$ indicates that the decrease in scatter in Roediger et al. (2017) is due to two points: for dwarfs brighter than $M_g = -16$ the difference in samples seems to dominate (the fact that Roediger et al. (2017) only have galaxies in the center of Virgo), while for fainter objects the SDSS colors are not accurate enough.

Our aim in this chapter is to make a detailed study of the origin of the scatter. To do this, we use the fact that HST photometry is very accurate, because of its photometric stability, and therefore use a sample of archival HST imaging data. We can study the origin of the scatter by comparing three clusters with each other, and by relating the position of a galaxy on the CMR with features in its images, such as the presence of dust, young stars, or galaxy truncations. The HST dataset is much better suited to do this with than any other currently in the literature.

In this chapter we discuss the CMR of three nearby clusters; Virgo, Fornax and Coma, in the luminosity range of $10^8 - 10^{9.5} L_\odot$, using high precision HST photometry. We use the HST archive images and calculate the magnitudes, effective radii and colors of the dwarf early-types in Fornax cluster. To compare the color-magnitude diagram of the Fornax early-type dwarfs with the corresponding ones in Virgo and Coma, we benefit from already existing color measurements in the literature. We discuss the CMRs, their scatter, outliers and how they are related to the cluster environment.

In Section 4.2, we discuss the sample selection and the data. We explain the method to calculate the colors and magnitudes in the Fornax cluster in Section 2.3. The CMR in these three clusters are presented in section 2.4. The origin of the scatter and the outliers of color-magnitude diagram are investi-

gated in Section 2.4.1. Finally we discuss the results in Section 2.5 and give some conclusions.

2.2 Sample Selection and Data

We selected three clusters for which high-quality the HST ACS data is available. For Fornax we obtained archival data from HST Mikulski archive. The list of galaxies is chosen from the ACS Fornax Cluster Survey (ACSFCS; Jordán et al. 2007a). The ACSFCS contains a magnitude-limited sample of 43 galaxies in the Fornax cluster selected from the Fornax Cluster catalog (FCC; Ferguson 1989) and observed with the ACS on HST. The field of view is about $202'' \times 202''$ and the pixel scale is $0.049''$

Here we included all the early-type dwarf galaxies in the sample of Jordán et al. (2007a). The magnitude limits are given by commonly accepted upper limits for dwarf galaxies ($M_B = -18$; Binggeli, Sandage & Tammann 1985) and lower magnitude limits of the Fornax ACSFCS sample. Using the distance modulus of $m-M=31.50$ of the Fornax Cluster (Table 3.1), these limits correspond to $13.5 \leq m_B \leq 15.5$. After calculating g' -band magnitudes on the ACS images, and using the same distance modulus, we found that the galaxies have magnitudes between $M_{g'} = -16.0$ and -18.7 . This sample selection leads to 26 dEs, for which we used their images in the F475W and F850LP bands. These two bands are similar to the SDSS g' and z' bands (Sirrianni et al. 2005). We therefore used the magnitude limit $-18.7 \leq M_{g'} \leq -16.0$ to select corresponding objects from Virgo and Coma.

For the Virgo cluster, we used HST Mikulski archival data. We selected our sample from the ACS Virgo Cluster Survey (ACSVCS; Côté et al. 2004), which observed 100 dEs in the Virgo cluster. They chose their sample from Virgo Cluster Catalog (VCC; Binggeli, Tammann & Sandage 1987) and considered the early-type galaxy classification in Sandage & Binggeli (1984) and some other conditions. We limited the selection to the same magnitude range as above for Fornax which provides us with 55 dwarf galaxies.

For the Coma cluster, we used the Coma ACS Survey (Carter et al. 2008), for which the photometry is described in Hammer et al. (2010). Since the sample of Hammer et al. (2010) consists of all types of galaxies in the fields of the Coma survey, including the nonmembers, we extracted the early-type members by cross-matching their sample with that of den Brok et al. (2011) whose sample of early-type galaxies are spectroscopically confirmed members as well as objects selected by eye as possible members. The same magnitude range as that used by Fornax and Virgo limits this sample to 40 early-type galaxies. The two filters used for the Coma HST observations were F475W and

Property	Fornax	Virgo	Coma	Reference
R_v (Mpc)	1.4	1.55	1.99(/h)	1,2,3
Mass($M_\odot$)	7×10^{13}	4.2×10^{14}	9.2×10^{14}	1,4,5
σ_v (Kms^{-1})	374	760	1200	1,6,7
Distance (Mpc)	20	16.5	100	8,9

Table 2.1 – Table of the parameters of the three clusters. Refrences: (1) Drinkwater et al. (2001), (2) Ferrarese et al. (2012), (3) Kubo et al. (2007), (4) McLaughlin (1999), (5) Falco et al. (2014), (6) Binggeli, Tammann & Sandage (1987), (7) Colless & Dunn (1996), (8) Blakeslee et al. (2009), (10) Carter et al. (2008).

F814W. The transformation between the colors, (F475W-F814W) to (F475W-F850LP), is discussed in Section 2.4.

Our final sample consists of bright dEs in the magnitude range of $-18.7 \leq M_{g'} \leq -16.0$ ($M_\star \sim 10^9 - 10^{10} M_\odot$) observed in g' and z' by the ACS on HST. The total numbers of the selected galaxies are 26, 54, and 40 in the Fornax, Virgo, and Coma clusters, respectively. One should note that in the Fornax and Virgo clusters, HST was pointed at individually selected galaxies, while in Coma, only a limited part of the cluster was observed, mostly in the central regions. This difference however does not make the samples incompatible, since both samples are still complete in this magnitude range. Although one should consider the Coma sample not as a sample representing the entire cluster, but mostly the cluster center. This should not be a problem, since Coma is used as a comparison cluster containing mostly old galaxies; furthermore, the way it is included now means that the fraction of old galaxies is probably even larger. In Figure 3.1 we present the radial distances of each object normalized by the Virial radius of its cluster (Table 3.1). This figure represents how the selected dEs are distributed in each cluster. The spatial resolution of the observations (corresponding to 1 pixel) is 5, 4, and 24 parsec in Fornax, Virgo, and Coma, respectively.

2.3 colors and magnitudes of bright early-type dwarfs

To calculate the color and magnitude of each galaxy in the Fornax cluster, we used Galphot, which is a surface photometry tool (Franx, Illingworth & Heckman 1989; Jorgensen, Franx & Kjaergaard 1992). We modeled the galaxy in the F475W and F850LP filters with an initial run of Galphot on the inner isophotes with varying parameters such as center, ellipticity, and position angle as a function of radius. We then performed the second run for each band by fixing these variables to the output values of the first run in the F850LP band.

Figure 2.1 – Histogram of the projected distance from the center normalized to the Virial radius of the cluster. Different colors are used for each cluster.

The final output is the surface-brightness profile of each galaxy in each band. Before running Galphot, the background of each image was calculated and subtracted using the mean of ten 4×4 (pixels square) boxes chosen randomly in the area around the masked galaxy, where we assumed that the contribution of the galaxy was minimal. We then slightly adjusted the background value, requiring the radial intensity growth curve to converge to a finite value. In this way, model-independent effective radii and total magnitudes were determined.

The $g' - z'$ (equal to F475W - F850LP) color is calculated in the AB photometric system. The zero points in g' and z' bands are from Sirianni et al. (2005). The color is determined in the range of $1'' < r < R_e$ to avoid background errors from becoming too dominant, and in most cases, to avoid the nuclear star clusters (for further information on nuclear clusters in Fornax from these data, see e.g. Turner et al. 2012). Table 2.2 lists our determined parameter values of the bright dEs in Fornax: FCC numbers, $g' - z'$ colors and their uncertainty, total absolute magnitudes, and effective radii in g' and z' bands. The average error in the color is 0.01 mag which combines background uncertainties in each band and zero point uncertainties.

Blakeslee et al. (2009) calculated g-z colors of Fornax early-type galaxies from the ACS HST data as well; they measured colors using annuli up to where the surface brightness of the galaxy is at least 60% of the sky level, whereas we

FCC number (1)	$R_e''(g)$ (2)	$R_e''(z)$ (3)	$g' - z'$ ($1'' < r < R_e$) (4)	$M_{g'}$ (5)	$M_{z'}$ (6)
FCC19	11.3	11.6	1.08 ± 0.01	-16.46	-17.57
FCC26	7.7	9.1	0.72 ± 0.02	-16.60	-17.47
FCC55	12.4	12.6	1.27 ± 0.01	-18.00	-19.29
FCC90	6.9	8.1	0.86 ± 0.01	-16.94	-17.89
FCC95	12.2	11.9	1.27 ± 0.02	-16.99	-18.25
FCC100	16.3	15.4	1.14 ± 0.02	-16.24	-17.33
FCC106	8.1	7.7	1.21 ± 0.02	-16.72	-17.89
FCC119	12.6	12.4	1.17 ± 0.02	-16.64	-17.80
FCC136	16.6	16.7	1.26 ± 0.02	-17.02	-18.29
FCC143	9.5	7.6	1.35 ± 0.01	-17.84	-19.09
FCC148	12.7	12.7	1.24 ± 0.01	-18.69	-19.92
FCC152	12.6	12.3	1.15 ± 0.01	-17.85	-18.99
FCC182	9.8	8.6	1.35 ± 0.01	-17.02	-18.29
FCC190	16.3	15.0	1.38 ± 0.02	-18.29	-19.61
FCC202	9.5	9.4	1.24 ± 0.02	-16.49	-17.74
FCC203	12.1	11.8	1.18 ± 0.03	-16.20	-17.36
FCC204	10.2	10.0	1.25 ± 0.03	-16.73	-17.97
FCC249	8.4	7.5	1.36 ± 0.01	-18.44	-19.75
FCC255	11.7	11.5	1.22 ± 0.01	-17.97	-19.19
FCC277	9.9	8.6	1.33 ± 0.01	-18.18	-19.40
FCC288	8.3	8.0	1.13 ± 0.02	-16.53	-17.58
FCC301	9.3	8.9	1.26 ± 0.01	-17.80	-19.04
FCC303	12.9	13.0	1.12 ± 0.02	-16.23	-17.36
FCC310	18.0	17.8	1.32 ± 0.01	-18.28	-19.60
FCC324	19.7	17.8	1.15 ± 0.03	-16.50	-17.60
FCC335	11.6	11.1	1.18 ± 0.01	-17.34	-18.49

Table 2.2 – Parameters of the dEs in Fornax determined here: (1) Name of the galaxy from the Fornax Cluster Survey, (2) and (3) Effective radius in g' and z' bands with an error of about 6%, (4) $g' - z'$ color in the range of $1'' < r < R_e$ and its error, (5) and (6) Absolute magnitude in g' and z' bands. The magnitudes and colors have been corrected for galactic reddening.

Figure 2.2 – Difference between tabulated $(g' - z')$ colors in Table 2.2 and calculated colors in Blakeslee et al. (2009) for Fornax vs. g' -band magnitude. The two outliers, FCC90 and FCC26, have very blue extended cores as it will be seen in next chapter.

consider the color up to one effective radius. These authors also excluded the innermost annuli $r < 1''$. Figure 2.2 shows the comparison of our calculated color versus Blakeslee et al. (2009). FCC26 and FCC90 are two very blue galaxies in our measurements. These galaxies have very extended blue cores as it will be discuss in next chapter. The fact that the apertures used by Blakeslee et al. (2009) are larger could explain this difference.

To check the accuracy of the effective radii, we show the ratio of the radii in g' - and z' -bands as a function of galaxy magnitude in Figure 2.3. Since FCC26 and FCC90 have very blue centers, which is further discussed in next chapter, $\frac{R'_{e,z}}{R'_{e,g}}$ is larger than 1. Most of the galaxies however show a ratio in the range of 0.8 to 1, implying a larger effective radius in the g' -band. These galaxies generally become bluer going outwards, that is, a negative color gradient which is discussed in detail in Section 3.4.3 in next chapter. This range of ratios is not unexpected (see e.g., Table 3 of Peletier et al. 1994, for ratios between effective radii in B and R in more massive galaxies). We also compared our determined effective radii in the g' band with those of Ferguson (1989) in the B-band in Figure 2.4.

For the Virgo cluster, we adopt the colors from Ferrarese et al. (2006); they

Figure 2.3 – Ratio of effective radii in g' - and z' -bands vs. absolute magnitude in g' -band. The dashed line is $\frac{R'_{e,z}}{R'_{e,g}} = 1$. The numbers on the data points are the FCC numbers.

Figure 2.4 – Ratio of effective radii of Ferguson (1989) to the effective radii in g' -band in this chapter vs. total magnitude of the galaxy in g' -band. The dashed line is $R_e(\text{Ferguson}) = R_e(\text{new})$.

determined them in the same radial range as we described for Fornax above ($1'' < r < R_e$). The photometric errors in Virgo given by Ferrarese et al. (2006) are much larger than what we derived here, since they gave errors on the total colors. However, inside R_e the surface brightness of the galaxies is generally so high that the errors in the magnitudes inside R_e are almost exclusively caused by errors in R_e . When one determines the errors in the color inside R_e , they almost completely vanish because the dependence on R_e vanishes. By concentrating on colors, we avoided the large (often 0.1 mag or larger) magnitude errors quoted in Ferrarese et al. (2006). Instead, for errors of the colors in Virgo, we used the average error of the early-type dwarfs in Fornax.

For the Coma cluster, the colors are tabulated by Hammer et al. (2010) from the HST/ACS data. As the closest magnitude system to ours in that paper is the Kron magnitudes, we used colors calculated in Kron aperture (1 Kron radius corresponds to 1.19 effective radius for an exponential surface brightness profile). For all three clusters, the photometry was corrected for Galactic extinction using the dust maps of Schlegel, Finkbeiner & Davis (1998) with the extinction law adopted by Jordán et al. (2004)(ACSVCS-II) from Sirianni et al. (2005):

$$A_g = 3.634E(B - V), \quad (2.1)$$

$$A_z = 1.485E(B - V). \quad (2.2)$$

For Fornax and Coma we used the same foreground extinction for the galaxies in each cluster, $\langle E(B - V) \rangle = 0.013$ and $\langle E(B - V) \rangle = 0.009$, as is reported in Jordán et al. (2007a) and Hammer et al. (2010). For Virgo we used different correction values for each galaxy tabulated in Ferrarese et al. (2006) with a mean $E(B-V)$ value of 0.028.

2.4 The color-Magnitude Relation

To compare the CMRs of these three clusters, we converted the Coma F814W data to the F850LP system using the following transformation, which is derived from Formula 1 in the Appendix of Roediger et al. (2017) :

$$(F475W - F814W) = 0.924(F475W - F850LP) - 0.027. \quad (2.3)$$

The resulting (F475W - F850LP) color corresponds to the SDSS $g' - z'$ color, with possible minor differences due to small differences in filter transmission curves.

Figure 2.5 – Color-magnitude diagram of bright dEs from Fornax (this study), Virgo (Ferrarese et al. 2006), and Coma (Hammer et al. 2010). The color codes of least-squares fitted lines are the same as for the points; red for Fornax, blue for Virgo, and green for the Coma cluster. The fitted lines in the upper panel are least-squares fits for each cluster. In the lower panel we fixed the slope of the fitted lines to the slope of the CMR in Coma as determined in the upper panel. All the parameters of the lines are given in Table 2.3. The VCC and FCC numbers of the red and blue outliers in the Virgo and Fornax clusters are indicated. The gray area shows the area of $\pm 2\sigma$ away from the CMR of Coma. The colors and magnitudes have been corrected for galactic extinction.

Upper panel: slope and intercept fitted			
Cluster	Slope(a)	y-intercept(b)	$\sigma(\text{mag})$
Fornax	-0.071 ± 0.017	1.250 ± 0.016	0.060
Virgo	-0.128 ± 0.022	1.323 ± 0.025	0.129
Coma	-0.073 ± 0.012	1.327 ± 0.011	0.065
Lower panel: only intercept fitted and fixed slope			
Fornax	-0.073	1.250 ± 0.013	0.060
Virgo	-0.073	1.277 ± 0.019	0.144
Coma	-0.073 ± 0.012	1.350 ± 0.011	0.065

Table 2.3 – Parameters of the fitted CMRs in Fig. 2.5 (upper and lower panel); $(g' - z') = a(M_{g'} + 18) + b$ and σ is the standard deviation.

Figure 2.5 shows the color–magnitude diagram (CMD) for the Virgo, Fornax, and Coma clusters. In the upper panel, we show the data points as well as three different least-squares fits to dEs of each cluster, taking into account the uncertainties in the photometry. In the lower panel we fit the CMR of the two other clusters with the slope fixed to the slope of the CMR of the Coma cluster. The parameters of these fits are given in Table 2.3. We applied an iterative sigma-rejection algorithm ($\sigma = 3$) to all three clusters before fitting the lines in both upper and lower panels, removing the bluest outliers.

The bottom panel of Fig. 2.5 shows that Fornax and Virgo are bluer than Coma. The second result is that the scatter with respect to the CMR is higher for the Virgo cluster. The standard deviations, σ , of the fitted lines to the Fornax, Virgo, and Coma are $\sigma = 0.060, 0.144, 0.065$ mag, respectively, after 3σ clipping. We discuss the interpretation of these results in the following section.

2.4.1 Reasons for the scatter in CMR

Considering the cluster masses (Table 3.1) and the morphology–density relation, one might expect the scatter in Coma to be the smallest, given the fact that the Coma galaxies were mostly selected from the center of the cluster, followed by Virgo and then by Fornax. Since galaxy formation would go faster in the most massive clusters (downsizing), the scatter caused by residual star formation should become smaller as clusters get more massive. However, in the previous section the scatter in Virgo was shown to be much higher than in Coma and Fornax.

Figure 2.6 shows a histogram of color residuals with respect to the CMR of Coma. For this we assumed that the CMR is a relation connecting the oldest galaxies for all magnitudes. A galaxy may lie blueward of the CMR when

Figure 2.6 – Distribution of the difference between the color of a galaxy in our sample and its expected color from the CMR of the Coma in Figure 2.5.

it has a younger effective age. In principle, a galaxy cannot lie on the red side of the CMR of early-types. We assumed that the CMR of Coma, as it is the reddest and the one with the least scatter, indicates this relation with the oldest galaxies. In this case, the color residual is a measure of the age difference between the oldest galaxy at a certain magnitude and the galaxy itself. To find outliers from the CMR we fitted a normal distribution on the color residuals of all three clusters together. Before fitting that, we clipped all the galaxies further than 3σ . After clipping, the Gaussian distribution has $\sigma = 0.09$. Here we defined red and blue outliers as galaxies that are located further than 2σ on both sides of the CMR; this area is shown in gray in the lower panel of Figure 2.5. Fornax has only blue outliers: FCC 26, FCC 90, and FCC 152. Virgo has some outliers on both blue and red sides: VCC21, VCC1192, VCC1261, VCC1488, VCC1499, VCC1695, VCC1779, and VCC1857 are on the blue side and VCC1327, VCC1297, and VCC1192 are on the red side. Coma has one bluer outlier: COMAi13005.684p275535.20. The names of these outliers are shown in the lower panel of Fig. 2.5.

Investigating the behavior of the outliers in Fig. 2.7, we found that the effective radii and the colors of the outliers are strongly correlated. This figure was made by determining the color and the radius that an average galaxy of a certain magnitude should have, using the color–magnitude and magnitude–effective

Figure 2.7 – Δcolor vs. normalized effective radius in g' for the bright dEs in Fornax, Virgo, and Coma. Δcolor is the difference between the color of a galaxy in our sample and its expected color from the CMR of the Coma cluster (color residual). Here the effective radius is divided by the expected radius from R_e vs. magnitude relations in each cluster: Eqs. 2.4, 2.5, and 2.6. The vertical dashed line corresponds to the CMR of Coma and the horizontal dashed line is $R_e = R_{ref}$. The gray area corresponds to the gray area of Figure 2.5.

radius relation of the sample. A least-squares fit gave us the following relation between g' -band magnitude and effective radius for Fornax, Virgo, and Coma clusters, respectively:

$$r_e(\text{kpc}) = -0.020 \times (M_{g'} + 18) + 1.16, \quad (2.4)$$

$$r_e(\text{kpc}) = 0.010 \times (M_{g'} + 18) + 1.10, \quad (2.5)$$

$$r_e(\text{kpc}) = -0.682 \times (M_{g'} + 18) + 4.28. \quad (2.6)$$

The effective radii of the galaxies in Coma are extracted from the HST Coma survey paper III (Hoyos et al. 2011). Δcolor is the difference between the color

of a galaxy from the CMR of the Coma cluster. We defined the normalized effective radius as the ratio of the effective radius in g' and the expected radius from the radius-magnitude relation. Plotting $\Delta color$ versus normalized effective radius, we found that there are three regions in Fig. 2.7: the galaxies with small $\Delta colors$ and normal radii, the ones that are redder than the CMR, which tend to have smaller radii than expected, and the ones that are bluer, which mostly tend to be smaller in size. The second group can be identified with the class of compact (red) dwarf ellipticals, while the third are dwarf ellipticals with young stellar populations, which are also more compact, as in for example BCD galaxies. We note that the second group (of compact dwarf ellipticals) does not contain any galaxies in Fornax and Coma, but several objects in Virgo. Apart from some exceptions, there is a visible trend that as galaxies become redder they also become smaller. VCC1661 is the galaxy with the largest effective radius (for a detailed study of this extended galaxy see Koch et al. 2017).

We first discuss the red outliers in detail. They are generally compact elliptical galaxies. These are objects like M32, with radii smaller than expected, and redder colors; they tend to be red, without any strong sign of young stellar populations (Gurou et al. 2015; Chilingarian et al. 2009). It is thought that these objects lost a significant amount of matter and light in an interaction, causing a truncated surface-brightness profile. The resulting color after the interaction is redder than expected for its radius, since the original galaxy was larger and therefore had a redder color. Furthermore, the central regions are generally redder, due to the color gradients in the original galaxies surviving the interaction.

To understand the outliers on the red side better, we take a closer look at them. All of the following outliers are Virgo early-type dwarfs: VCC 1192, VCC 1297, and VCC 1327. There are two additional red galaxies very close to the 2σ threshold from Virgo: VCC 1627 and VCC1871. From Ferrarese et al. (2006), VCC 1192 is a close companion of the massive elliptical, M49, with a projected distance of $4'.2$ (~ 20.2 kpc). Similarly, VCC 1297 and VCC 1327 are at the projected distances of $7'.3$ and $7'.5$ ($\sim 35.1, 36.1$ kpc) from M87. All three galaxies are near giant companions and could be tidally truncated by interactions with their massive neighbors. Interestingly, Gurou et al. (2015) classified VCC 1192 and VCC1297 as compact early-type galaxies. It looks as if most, and perhaps all, of the red outliers are compact dwarfs. In Gurou et al. (2015) there are more compact galaxies from Virgo that are slightly redder or are on the CMR in our plot: VCC1178, VCC1440, VCC147, and VCC1627; although they are not counted as red outliers here as they are in the 2σ shaded area. To conclude, we found three outlying red galaxies in the Virgo cluster more than 2σ away from the CMR of Coma.

On the blue side of the CMR, there are also several outliers that have been discussed extensively in the literature; by for example Lisker et al. (2007). These are objects that still contain a considerable fraction of young stellar populations, even though they have been classified as dEs. In next chapter, we show the unsharp masked images of these galaxies from the Fornax cluster. It is clear from their unsharp masked images that they have extended star forming regions. FCC26 and FCC90 are both also bright in GALEX UV, indicating young stars (Gil de Paz et al. 2007). Dwarfs with younger stellar populations lie on the blue side of the CMR in most cases. In addition, VCC1499 is highlighted by Boselli & Gavazzi (2014) as an example of a galaxy with a "post-star-burst" spectrum.

Since the colors provide us with crude information about the galaxy ages, we can estimate the age difference between galaxies in the clusters by assuming that galaxies consist of a single stellar population. For a typical dE metallicity, $Z=0.004$ (Ryś et al. 2015), the models of Bruzual & Charlot (2003) predict $\Delta(g' - z')/\Delta(\log Age) = 0.575$. An offset of $\Delta(g' - z') = 0.102$ (Table 2.3) for Fornax regarding the Coma CMR corresponds to a difference in age of about 1.5 Gyr. On average, the early-type dwarfs in the center of Coma are therefore 1.5 Gyr older than the ones in the Fornax and Virgo clusters.

We applied a Kolmogorov-Smirnov (K-S) test to investigate whether age distributions of the three clusters are similar within the errors; we compared two clusters each time. The outcome probabilities, p-value, indicate whether or not these ages are drawn from the same distribution: $p=0.032$, 0.0001 and 0.008 , respectively, for (Fornax, Virgo), (Fornax, Coma) and (Virgo, Coma) pairs. These tests indicate that the age distribution of dEs in Coma is statistically different from the age distributions of dEs in Fornax and Virgo; the latter two have more similar age distributions.

2.5 Discussion and Conclusion

In this chapter, we calculated and tabulated the magnitudes, colors and effective radii of bright dwarfs in the Fornax cluster from the high quality HST observation. We then compared the CMD of early-type dwarfs in the Fornax cluster with similar-size galaxies in Virgo and Coma. Since the observational errors are small, because of the photometric precision of HST, we have been able to study the scatter in the CMR in detail and compare the three clusters. We find that the scatter in the CMR in Virgo is considerably larger than in Fornax and Coma. The scatter is due to the presence of young stars, causing galaxies to lie blueward of the CMR, and by compact early-type galaxies, which lie redward of it. We also find that the CMR of Fornax and Virgo are considerably bluer than the CMR of Coma. We will discuss these results more

in the next paragraphs.

The CMR of the early-type galaxies in nearby clusters and its scatter have been studied for several decades (e.g. Sandage 1972; Sandage & Visvanathan 1978). For massive galaxies Schweizer & Seitzer (1992) showed that the blueward deviation from the CMR correlates with a so-called fine structure index. It is a morphological indicator of recent mergers, with presence of younger stars, establishing that galaxies evolve towards a tight color-magnitude relation, which was later called the red sequence (Bell et al. 2004). For dwarf galaxies a thorough investigation of dwarf ellipticals in the Virgo cluster, Lisker et al. (2006) showed that more than 15% of the bright dwarfs ($m_B \leq 16$) in Virgo have a blue central population superimposed on an otherwise red galaxy. A study by Janz & Lisker (2009) found that the intrinsic scatter increases from $M_r = -20$ to $M_r = -17$, and then decreases again at fainter magnitudes. When calculating this intrinsic scatter, they do not take into account galaxies with blue centers, but redder than the red sequence are included, leading to their conclusion that the CMR in Virgo displays a considerable intrinsic scatter in the region of bright dwarfs. Recently, using deep optical imaging from the Next Generation Virgo Cluster Survey (NGVS, Ferrarese et al. 2012), Roediger et al. (2017) study the red sequence of the galaxies in a central area of about $2^\circ \times 2^\circ$ of the Virgo cluster in the $u^*g'i'z'$ bands. They identify that a very high fraction of their bright galaxies ($M'_g \geq -15$) shows clear signs of star formation, while 3 of their bright dwarfs are compact, or stripped, as they mentioned. Even ignoring these objects, their CMR for the other objects, for which they do not find any signs of young stars, has non-zero scatter, in agreement with the photometry of Janz & Lisker (2009) for the same objects. We confirm this picture of Janz & Lisker (2009) and Roediger et al. (2017) that the CMR of Virgo has non-zero scatter. In this chapter we use HST data, which allows us to detect young stellar populations and extinction more accurately, so that a better idea is obtained about how galaxies form and evolve.

We note several galaxies lying significantly below the red sequence, defined as the best-fitting linear relation to the CMD of early-types. Considering the images of the galaxies which are significantly bluer than the CMR, we found signs of young stellar populations and dust extinction features. The Virgo cluster, apart from having some galaxies lying below the CMR, also has many galaxies that lie above the red sequence which they do not exist in Fornax and Coma. Most of the blue and all of the red outliers have smaller effective radii than expected for galaxies on the red sequence.

All of the red outliers are compacts and their projected locations are very close to a massive companion galaxies. Compact elliptical galaxies (cEs), of which M32 is the 'prototype', have often been thought to be truncated because of in-

interactions with larger companions (e.g. King 1962; Bekki et al. 2001; Price et al. 2009). There are not many known cEs. Chilingarian et al. (2009) performed a search using the virtual observatory finding 14 confirmed compact elliptical galaxies, none of which showing any young stellar populations. Guérou et al. (2015), in an Integral Field Unit (IFU)-study of compact ellipticals, also find that only one of their 8 targets has stellar populations of ~ 3 Gyr, while the rest is older than 6 Gyr. Two of their seven objects in common are clearly redder than the red sequence in our paper. Using a sample of compact stellar systems and comparing them with globular clusters, and giant and dwarf galaxies, Janz et al. (2016) claimed that cEs are stripped massive galaxies, considering the fact that they have similar metallicities to dwarf nuclei and the center of massive early-type galaxies. They also reported that the outliers in the mass-metallicity relation are cEs (see Janz et al. 2016, Figure 5), similar to what we showed here for red outlier compact dwarfs. Although the above scenario seems to explain the way the cEs form in Virgo, it is not the only formation theory.

All the red outliers in Virgo are compact early-type galaxies based on their effective radii, and are close companions to massive neighbors. Given the number of the red outlier cEs in Virgo cluster, one might expect there to be a similar number in the Coma and Fornax clusters. If the probability of finding red outlier cEs is the same in all three clusters, we would expect to have 2 ± 1 in Coma and 1 ± 1 in Fornax. The probability of finding zero red outliers in Coma is 10% and for Fornax, it is 23%. As discussed in Section 2.4.1, we did not find any in Coma or Fornax. Different statistics of compact dwarf galaxies in these clusters can provide a hint to their formation mechanism. One should keep in mind that ultra compact dwarfs are not considered here, since they fall outside our magnitude range (Drinkwater et al. 2000).

Here we used three clusters with distinct characteristics. Comparing the cluster's environment, Coma is a relaxed, dense and rich cluster at a distance of 100 Mpc (Carter et al. 2008). It is much denser than the less relaxed Virgo cluster. The density of a galaxy's environment play an important role in its star formation and quenching and from there in its color; i.e. a denser environment produces more effective gas removal through all tidal forces which quench star formation and push the galaxy to the red sequence faster. Fornax at a distance of 20 Mpc is six times less massive, smaller, more regular in shape and has a shallower potential well compared to Virgo (Jordán et al. 2007a). The velocity dispersion of Fornax is lower compared to Virgo and Coma (Table 3.1). These environmental differences can be the reason for the bluer CMR of Fornax and higher scatter of the Virgo cluster, shown in Figure 2.5.

A denser environment can also compress the gas through the ram pressure

or harassment and induces star formation in the galaxy (Sybilska et al. 2017; Tonnesen & Bryan 2009). Virgo is an active and irregular cluster with a young dynamical nature (Mei et al. 2007; Binggeli, Popescu & Tammann 1993; Drinkwater et al. 2001; Conselice, Gallagher & Wyse 2001). Sybilska et al. (2017) interpret that Virgo has a non symmetric density distribution by studying the number density map of the cluster. Several galaxies in this cluster experience ram pressure stripping by the intracluster medium which quenches their star formation activity and makes them red (e.g. Forman et al. 1979; Boselli et al. 2014). For the Virgo cluster, a dynamically evolving, young environment with effective interactions, may explain the scatter and outliers seen in the CMD.

We must also note that our sample of dEs in Coma used in this study is mostly from the central region of the cluster as the ACS camera failed during the later stages of the survey. Studies show that the color of a galaxy correlates with the density of its environment; redder galaxies reside in denser environments (Gavazzi et al. 2013; Boselli & Gavazzi 2014). Since the galaxies in the center of the cluster have entered the environment earlier and have gone through more environmental influences, they have less star formation (Sybilska et al. 2017; Lisker et al. 2013). This could well be the reason behind fewer blue outliers in Coma in Figure 2.5.

We conclude stating the main results of this chapter. We discussed the origin of the scatter in the CMR, by using high quality HST data for 3 nearby galaxy clusters.

- We found that in the magnitude interval of $-18.7 \leq M_{g'} \leq -16.0$, the scatter in the CMR is the highest in Virgo, 0.144 mag. In Fornax and Coma the scatter is 0.060 and 0.065 mag, respectively. The large number of outliers on its blue side shows that the Virgo cluster dwarfs are still quite actively forming stars. The same is true for the Fornax cluster.
- The situation with the red outliers is totally different in Virgo, as compared to the other clusters. All the red outliers of the color–magnitude diagram in the Virgo cluster are compact ellipticals. Their redder color can probably be explained by tidal interactions with large nearby massive galaxies. There are three red outlier compact galaxies in Virgo and none in the Fornax and Coma clusters. The fact that there are more red outliers in Virgo, a cluster with more ongoing interactions, and that these are cEs, probably means that the environment is still very active, with many galaxy–galaxy interactions, more than in the other clusters. To fully test this idea, much larger sample sizes are needed for statistical significance.
- The scatter on the blue side of the CMR is due to galaxies with young stellar populations. This is mainly the case in Fornax and Virgo. Their fractions are $11\% \pm 2\%$, $15\% \pm 3\%$, and $2\% \pm 1\%$ of the total dwarf early-type galaxies in

Fornax, Virgo, and the central regions of Coma, respectively. The galaxies in Fornax and Virgo in general are probably somewhat younger.

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Young stellar populations in early-type dwarf galaxies; a comparison between the Fornax, Virgo and Coma clusters

Elaheh Hamraz^{a, b}, Reynier F. Peletier^a, Habib G. Khosroshahi^b, Edwin A. Valentijn^a, Mark den Brok^c, Aku Venhola^{a, d}

^a Kapteyn Astronomical Institute, University of Groningen, Postbus 800, NL-9700 AV Groningen, the Netherlands

^b School of Astronomy, Institute for Research in Fundamental Sciences (IPM), Tehran, 19395-5746, Iran

^c Leibniz-Institut für Astrophysik Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany

^d Astronomy Research Unit, University of Oulu, Oulu, FI-90014 Finland

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Abstract

In this study, we use Hubble Space Telescope Advanced Camera for Surveys for the Fornax, Virgo and Coma clusters to describe and parameterize the $(g - z)$ color profiles of dwarf early-type galaxies in the magnitude range of $-18.7 \leq M_B \leq -16.0$. The important result of this paper is the large amount of dwarf early-types with young stellar population in their center in all three clusters: the whole sample in Fornax, $85\% \pm 2\%$ in Virgo and $53\% \pm 3\%$ in the Coma cluster. We show that bluer cores reside in fainter dEs, similar to the trend seen in nucleated dEs. We find no correlation between the luminosity of the galaxy and the size of its blue core. Considering the very distinct characteristics of these clusters and the distribution of these galaxies in each cluster, their formation and evolution are influenced by different factors and cannot be explained by a single theory.

3.1 Introduction

Dwarf early-type galaxies are small, low-luminosity galaxies ($M_B \geq -18$) (Ferguson & Binggeli 1994) with a shallow potential well that makes them sensitive to their environment. Early studies (e.g., Ferguson & Binggeli 1994) assumed that dEs are gas-free galaxies, however as our understanding of these galaxies improved, it was found that not all the dEs are quiescent galaxies with smooth surface brightness, elliptical isophotes, and regular appearance, since some spiral structure, recent or ongoing star formation, gas, and dust content are reported in some of them (De Looze et al. 2010; Lisker et al. 2006; Grebel 2001; Jerjen, Kalnajs & Binggeli 2000; Hodge 1973). Some studies have even reported the detection of H I in some of these galaxies (Conselice et al. 2003; Gavazzi et al. 2003). In addition, Lisker et al. (2006) showed clear signs of star formation in these galaxies by using SDSS spectra. The star formation histories of dEs are diverse and are dependent on environment (e.g., Tolstoy, Hill & Tosi 2009).

The fact that dEs show signs of star formation is not new (Vigroux, Souviron & Vader 1984). Studying young populations in early-type galaxies, Peletier (1993) reported on dust and a recent star forming region in the center of the dE NGC205 (Messier 110); he presented radial color profiles in various colors and showed that they drop toward the center of the galaxy (Fig 3, Peletier 1993). Durrell (1997) investigated two dEs in Virgo with CFHT and found one of them to have a bluer nucleus than the galaxy. Taking advantage higher-resolution data, Lotz, Miller & Ferguson (2004), for a sample of dEs in the Leo Group, the Virgo and Fornax clusters, observed with the Hubble Space Telescope (HST) WFPC2, showed that the nuclei of dEs are bluer than their underlying galaxies. In the Virgo cluster and using SDSS data for galaxies with $M_B \leq -13$, Lisker et al. (2006) noticed that about 5% of dEs have a blue center. This number is more than 15% among dEs with $M_B \leq -15$. Pak et al. (2014) found that about 70% of dEs in their Ursa Major sample have a young core with blue UV-optical color, an indication of recent or ongoing star formation in their centers (Gu et al. 2006; De Rijcke, Buyle & Koleva 2013).

Studying the formation of stellar populations in the inner parts of dEs could lead us to find some clues about the origin of these galaxies and the role of the environment in their evolution. On the one hand, galaxy properties correlate with their environment. Ram pressure stripping, strangulation, merging, tidal interaction and harassment are among the important processes happening in the cluster and changing the properties of the galaxies. Boselli & Gavazzi (2014) explained that the strong gravitational potential well in the core of these galaxies might keep the gas needed for recent star formation in the stripped galaxies and make the center blue. Recently, Zabel et al. (2019) as part of

the Atacama Large Millimeter Array (ALMA) Fornax Cluster Survey, studied the CO(1-0) line as the cold molecular gas tracer which shows star formation. These latter authors reported disturbed morphologies and kinematics for several of their CO detected galaxies. Ram pressure stripping is considered the most probable cause of these disturbed morphologies, which shows the role of clustal environment in their evolution. One of the most popular formation scenarios entails infalling late-type galaxies that interact with the cluster environment and transform to blue-cored dEs (Boselli et al. 2008; De Rijcke, Van Hese & Buyle 2010; Lisker et al. 2006; Mastropietro et al. 2005). In some other scenarios, gas-rich irregulars are thought to have merged and formed dEs. Pak et al. (2014) suggested that the blue-cored dEs could be a possible object in transition of a late-type galaxy to a red early-type. On the other hand, considering similarities between the Virgo and Fornax nuclei versus their different environment, Turner et al. (2012) concluded that the formation of blue-cored dEs is more dependent local factors of the galaxies than on their residing environment.

Taking advantage of the high-resolution imaging of HST, an object as small as a nucleus of a dwarf galaxy can be distinguished in the nearby clusters further than our local group. Since the size of these blue cores is comparable with the nuclei found by the HST survey of the nearby clusters, reviewing the results of this latter survey could help our investigation. Lotz, Miller & Ferguson (2004) used F555W and F814W bands and studied nuclei and globular clusters of 69 dwarf ellipticals in the Virgo and Fornax Clusters and the Leo Group. Defining the nucleus as a bright compact object in the region of $1.5''$ from isophotal center, these latter authors noted that most of the nuclei are bluer than their host galaxies. They did not find any correlation between the projected distance from the center of the cluster and the properties of the nuclei and claimed that brighter dEs have deeper potentials and are able to attract gas into their centers, which can explain the reason why redder and brighter dEs have redder and more luminous nuclei. Comparing the nuclei of dEs in Fornax and Virgo, Lotz, Miller & Ferguson (2004) could not find any considerable differences.

There are more studies which used HST images to go down to the size of the nuclei. Following the Advanced Camera for Surveys (ACS) Virgo cluster survey, Côté et al. (2006) investigated size, color, and some other properties of the nuclei of dEs in the Virgo cluster using F475W and F850LP bands. These latter authors concluded that the number of galaxies with a bluer nucleus in their sample is between 66% and 82%. They found many more nucleated dEs than previous studies and came to the conclusion that since the color and the luminosity of the nuclei are strongly correlated and rarely relate to their host galaxies, the formation and enrichment of galaxies are more closely linked to

internal factors.

The nuclei of the early-types in the Fornax cluster have also been studied using HST resolution. As part of the ACSFCS collaboration, Turner et al. (2012) found that most low- and intermediate-luminosity early-type galaxies in their sample show excess light in their central part. Similar to the previous studies, they also confirm that the nuclei are mostly bluer than their host galaxies, or at least 72% of them, and bluer hosts have bluer nuclei and vice-versa. Comparing their sample with Côté et al. (2006), they concluded that the similarities of the nuclei of these two clusters is an argument showing that the environment does not play a role in their formation and evolution.

In the previous chapter, we presented precise color-magnitude diagram of the bright dwarf early-types in the magnitude range of $-18.7 \leq M_{g'} \leq -16.0$ in the Fornax, Virgo and Coma clusters and the effect of their environments on it. We benefited high quality imaging of the Advanced camera for surveys (ACS) on HST in F475W and F850LP bands to understand the reason of the scatter and outliers of the CMR. Unlike the normal dwarf early-types, the outliers in blue side, mainly in Fornax and Virgo, are shown to have extended dust and star forming regions in their centers. The other more engaging result is the red outliers which are shown to be compact dwarf early-types and we found several of them in Virgo. Since most of the detected compacts are projected near the massive galaxies, tidal truncation could be a convenient scenario for their formation (Chilingarian et al. 2009; Guérou et al. 2015). We noted the scatter of CMR in Virgo cluster is higher and together with its outliers, we suggested that it is a consequence of the dynamically active nature of its environment.

Following the first chapter, here we aim to determine the gradient in old population (seen in the outer part) as well as the central young population. Since the galaxies core have the clue of violent process that has happens to the central region, studying them will shed light on our understanding of the formation and evolution of dwarf early-types. As den Brok et al. (2011) noticed, excluding the center of early-type galaxies can influence the color gradient which is a key to distinct stellar population of the core. Distinguishing the core of a dwarf early-type in nearby clusters (as small as a few 10 pc), is rarely possible with the sharpest ground based telescopes (Grant, Kuipers & Phillipps 2005). Ground-based telescopes in general cannot go further inwards than $1''$, which is about 100 pc at the distance of Fornax. Distinguishing the core of a dE in nearby clusters (as small as a few tens of pc) is rarely possible with the sharpest ground-based telescopes (Grant, Kuipers & Phillipps 2005). The ACS camera on HST makes it possible to resolve a small nucleus with $R_e \sim 0''.025$ (Côté et al. 2006). Taking advantage of the resolution of HST and the sufficient separation in wavelength of the F475W and F850LP HST bands to study young

stellar populations, we can now investigate in more detail the color of the very inner part of dEs in nearby clusters. To discuss the effect of the cluster environment, we choose three clusters with distinct characteristics, all of which have been studied by HST: Virgo, Fornax, and Coma.

The outline of this chapter is as follows. In Section 4.2, we present the selected sample of dwarf early-type galaxies from the Fornax, Virgo and Coma clusters which is the same sample as previous chapter. Isophotal analysis of photometric images of our sample is covered in Section 3.3. The results of the analysis contain various photometric parameters of the galaxies in the samples and the comparison of these parameters in these three clusters is given in Section 3.4. Section 3.5, discusses and summarizes the results. More tables and outcome plots can be found in Appendix.

3.2 Sample Selection and Data

We selected three clusters for which high-quality the HST ACS data is available. For Fornax we obtained archival data from HST Mikulski archive. The list of galaxies is chosen from the ACS Fornax Cluster Survey (ACSFCS; Jordán et al. 2007a). The ACSFCS contains a magnitude-limited sample of 43 galaxies in the Fornax cluster selected from the Fornax Cluster catalog (FCC; Ferguson 1989) and observed with the ACS on HST. The field of view is about $202'' \times 202''$ and the pixel scale is $0.049''$

Here we included all the early-type dwarf galaxies in the sample of Jordán et al. (2007a). The magnitude limits are given by commonly accepted upper limits for dwarf galaxies ($M_B = -18$; Binggeli, Sandage & Tammann 1985) and lower magnitude limits of the Fornax ACSFCS sample. Using the distance modulus of $m-M=31.50$ of the Fornax Cluster (Table 3.1), these limits correspond to $13.5 \leq m_B \leq 15.5$. After calculating g' -band magnitudes on the ACS images, and using the same distance modulus, we found that the galaxies have magnitudes between $M_{g'} = -16.0$ and -18.7 . This sample selection leads to 26 dEs, for which we used their images in the F475W and F850LP bands. These two bands are similar to the SDSS g' and z' bands (Sirrianni et al. 2005). We therefore used the magnitude limit $-18.7 \leq M_{g'} \leq -16.0$ to select corresponding objects from Virgo and Coma.

For the Virgo cluster, we used HST Mikulski archival data. We selected our sample from the ACS Virgo Cluster Survey (ACSVCS; Côté et al. 2004), which observed 100 dEs in the Virgo cluster. They chose their sample from Virgo Cluster Catalog (VCC; Binggeli, Tammann & Sandage 1987) and considered the early-type galaxy classification in Sandage & Binggeli (1984) and some other conditions. We limited the selection to the same magnitude range as

Property	Fornax	Virgo	Coma	Reference
R_v (Mpc)	1.4	1.55	1.99(/h)	1,2,3
Mass($M_\odot$)	7×10^{13}	4.2×10^{14}	9.2×10^{14}	1,4,5
σ_v (Kms^{-1})	374	760	1200	1,6,7
Distance (Mpc)	20	16.5	100	8,9

Table 3.1 – Table of the parameters of the three clusters. Refrences: (1) Drinkwater et al. (2001), (2) Ferrarese et al. (2012), (3) Kubo et al. (2007), (4) McLaughlin (1999), (5) Falco et al. (2014), (6) Binggeli, Tammann & Sandage (1987), (7) Colless & Dunn (1996), (8) Blakeslee et al. (2009), (10) Carter et al. (2008).

above for Fornax which provides us with 55 dwarf galaxies.

For the Coma cluster, we used the Coma ACS Survey (Carter et al. 2008), for which the photometry is described in Hammer et al. (2010). Since the sample of Hammer et al. (2010) consists of all types of galaxies in the fields of the Coma survey, including the nonmembers, we extracted the early-type members by cross-matching their sample with that of den Brok et al. (2011) whose sample of early-type galaxies are spectroscopically confirmed members as well as objects selected by eye as possible members. The same magnitude range as that used by Fornax and Virgo limits this sample to 40 early-type galaxies. The two filters used for the Coma HST observations were F475W and F814W. The transformation between the colors, (F475W-F814W) to (F475W-F850LP), is discussed in Section 2.4.

Our final sample consists of bright dEs in the magnitude range of $-18.7 \leq M_{g'} \leq -16.0$ ($M_\star \sim 10^9 - 10^{10} M_\odot$) observed in g' and z' by the ACS on HST. The total numbers of the selected galaxies are 26, 54, and 40 in the Fornax, Virgo, and Coma clusters, respectively. One should note that in the Fornax and Virgo clusters, HST was pointed at individually selected galaxies, while in Coma, only a limited part of the cluster was observed, mostly in the central regions. This difference however does not make the samples incompatible, since both samples are still complete in this magnitude range. Although one should consider the Coma sample not as a sample representing the entire cluster, but mostly the cluster center. This should not be a problem, since Coma is used as a comparison cluster containing mostly old galaxies; furthermore, the way it is included now means that the fraction of old galaxies is probably even larger. In Figure 3.1 we present the radial distances of each object normalized by the Virial radius of its cluster (Table 3.1). This figure represents how the selected dEs are distributed in each cluster. The spatial resolution of the observations (corresponding to 1 pixel) is 5, 4, and 24 parsec in Fornax, Virgo, and Coma, respectively.

Figure 3.1 – Histogram of the projected distance from the center normalized to the Virial radius of the cluster. Different colors are used for each cluster.

3.3 Analysis

3.3.1 Isophotal analysis of the galaxies

To accurately investigate the substructure in the stellar populations of each galaxy, radial color profiles were determined. This process was done for the Fornax and Virgo galaxies, while for the Coma cluster we simply adopted the output of Galphot from den Brok et al. (2011) who did the same procedure as above to calculate the color profiles. All the color profiles are sky subtracted. It is important to mention that the color obtained in the centers of the galaxies, which this paper is interested in, is very sensitive to the point spread function (PSF) of the data. We convolved the image of the galaxy in each band with the PSF of the other band before running Galphot on them, in the same way as was done in Peletier et al. (2012), for example. The PSFs used here are generated by the Tiny Tim HST PSF software (Krist, Hook & Stoehr 2011).

The unsharp masking technique is a well-known method to study the substructure of a galaxy. An unsharp mask is the original image divided by the smoothed one. This method amplifies high-frequency components of the image which provides a more reliable and clear detection of gas, dust features, and asymmetric star formation regions compared to the residual image (Lisker et al. 2006). We produce unsharp masked images of the Fornax galaxies by

smoothing them with a two-dimensional circular Gaussian of a kernel size of $\sigma = 20$ pixels (1 arcsec). In most cases the unsharp masked images show central irregularities which are caused by gas and dust features or regions of young stellar populations.

Another method for extracting substructures involves identifying them on a color map of the galaxy, which is made using the images of the galaxy in two different filters. In Figure 3.2, we present the unsharp masked and color maps of our Fornax sample.

In addition to making unsharp masked and color images of the galaxies, aperture photometry is used to check the color profile results. For this aim, we use the APPHOT task of the IRAF, a set of tasks for performing aperture photometry on uncrowded or moderately crowded fields. The photometric technique employed is fractional pixel integration (Davis 1994). The magnitude of the galaxies for two different radii 2 and 4 pixels ($= 0.1'', 0.2''$) are calculated regarding each band's zero point. Here, the galaxy center is determined by "centroid" centering algorithm which computes the intensity weighted mean of the marginal profiles in x and y.

3.4 Results

3.4.1 Color profiles and calculated parameters

The color profiles of 26 early-type dwarf galaxies in the Fornax cluster are shown in Figs. 3.2 to 3.7. In these profiles, the color is ($F475W - F850LP$) in AB-mag. The radius (r) is the circularized distance of each fitted ellipse, $r = \sqrt{ab}$, where a and b are semi-major and semi-minor axes of the ellipse. We fitted a color-log(r) line to the color of the outer part of the galaxy shown by the red line in the color profiles of Fig. 3.2. This line fits better to the outer parts of the color profiles, similar to the way explained by den Brok et al. (2011). We used an error-weighted least-squares method to fit these lines. For each color profile, the red fitted lines are extrapolated inward. We started our color profiles at 1 pixel equal to $0.05''$ and continued in radius as far as $0.8R_e$. The effective radii and total magnitudes in g' are from Table 2.2.

For most dEs in the Fornax cluster sample, the color profiles are getting slightly bluer going outward. den Brok et al. (2011) and also Peletier et al. (2012) interpreted the outer bluing as an effect of old stellar populations for which the metallicity is slowly decreasing outward. The green line in Fig. 3.2 shows the color this galaxy would have if it were exactly on the CMR of Fornax (previous chapter). In the center of the galaxies, the profile drops down making a blue central region. The black vertical lines show the starting point of the core inside which the color profile does not follow the slope of the outer part. These

Figure 3.2 – Color profiles (color- $\log(r)$) and unsharp masked in g-band and color images of the Fornax early-type dwarf galaxies. In the color profiles, the green line shows the color of the CMR in that magnitude. The red line is fitted to the outer part of the profile and the black dashed line separates the inner part from the outer part of the galaxy. The width of the unsharp masked and the color images is $26''$ and the color of the unsharp masked image is inverted.

Figure 3.3 – 3.2 Continued

Figure 3.4 – 3.2 Continued

Figure 3.5 – 3.2 Continued

Figure 3.6 – 3.2 Continued

Figure 3.7 – 3.2 Continued

points were chosen by eye. den Brok et al. (2011) defined it as the center which has been excluded in their color gradient calculation to have a better-fitted line to the outer part of a galaxy. In some cases, the color profiles do not follow this shape and they have a very extended bluer area; for example, FCC 26, FCC 90, and FCC 152. For these galaxies, it is clear from their unsharp masked and color images that they contain a large and extended amount of dust and young stellar populations. Since the previous scheme is not appropriate in such cases, we did not fit a line to their profiles.

The unsharp masked and color images of each galaxy are shown in the right-hand side of the corresponding color profile in Fig. 3.2. The width of their boxes are $26''$. Galaxies with extended blue cores, such as FCC26, FCC90, FCC119, FCC152 and FCC335, have young stellar populations and dusty regions in their unsharp masked and color images. According to the color images, some of the galaxies have a very well-defined blue center, that is, FCC148 and FCC204.

To quantize better these color profiles, we determined various parameters. The color gradient, the slope of the fitted red line, is one of the calculated parameters. A positive (negative) color gradient indicates that the galaxy has a redder (bluer) color as it goes outward. Another parameter is the excess light of the core from the fitted line to the outer region. In the color profiles, it is the average of the difference between the color of the center, separated by the black vertical line, and the extrapolated dashed red line:

$$\begin{aligned}
X_{outer\ fit} &= \langle Color_{galaxy} - Color_{red\ line} \rangle \\
&= -2.5 \log_{10} \frac{\int 10^{-0.4(color_{galaxy} - color_{red\ line})} I_{F475W} dA}{\int I_{F475W} dA} \quad (3.1)
\end{aligned}$$

where I_{F475W} is the intensity in F475W band. This average is calculated between the start point of the radius of the color profile and the dashed black line, that is, the central part of the galaxy. Positive (negative) amounts generally show that the center of the galaxy is redder (bluer) than the fitted line to the outer part. A similar formula is used to find the excess light from the CMR line, the green line in color profiles, for the whole profile, $X_{CMR} = \langle Color_{galaxy} - Color_{CMR} \rangle$. In this parameter, which we call excess light from the CMR line, a positive (negative) sign implies that the galaxy, in total, is redder (bluer) than the CMR.

Table 3.2 lists the measured parameters for our sample of the Fornax cluster. For the three galaxies without the fitted red line, we considered the green line to be the reference color of their older population, where we can calculate the excess bluer light of the center from there. In this case, $X_{outer\ fit} = X_{CMR}$. Their core sizes are equal to the end point of the color profile. The color gradient of the fitted line for these extended cases is set to n in the table.

For the Virgo cluster, we applied the same procedure. The color profiles of the dEs in Virgo with the same color-log(r) line fitted to the data are shown in Figure 3.14 in the Appendix. The resulting parameters are listed in Table 3.3 and 3.4, which similar to Table 3.2. We note that in Table 3.3, when there is no fitted line to the color profile, as is the case for the galaxies with extended blue centers, the core size, the excess light from the fitted line and the color gradient are as explained in the previous paragraph. For the galaxies without a core, the core size and the excess light from the fitted line are displayed by n in the table.

The position of the galaxies on the CMR of the Virgo galaxies is given in color-magnitude relations table in the previous chapter and is shown by the green horizontal line in the color profiles. For some cases, Côté et al. (2006) noted that the color of their nucleus is quite blue; For VCC21, for example, this is (F475W-F850LP)= 0.3, which is consistent with its color profile in Fig 3.14 of this chapter. These latter authors interpreted this galaxy as dIrr/dE transition type with a blue nucleus younger than 1 Gyr for any selected metallicity.

The output of the Galphot task in the two different bands for each galaxy from den Brok et al. (2011) is used to re-plot the color profiles to determine the same parameters for our Coma sample, Figure 3.21 in the Appendix. A color-log(r) line is fitted to the color profile of the galaxies in Coma to calculate the excess light in the same way as in Fornax and Virgo. A similar color-

FCC number (1)	Blue galaxy (2)	Blue core (3)	r_{core} (pc) (4)	$X_{outer\ fit}$ (5)	X_{CMR} (6)	$\nabla(g' - z')$ (7)
FCC 19	Y	Y	44	-0.09	-0.07	0.063 ± 0.005
FCC 26	Y	Y	707	-0.47	-0.47	n
FCC 55	Y	Y	34	-0.04	0.00	-0.003 ± 0.002
FCC 90	Y	Y	746	-0.40	-0.40	n
FCC 95	N	Y	36	-0.05	0.09	-0.029 ± 0.003
FCC 100	Y	Y	36	-0.11	0.00	0.063 ± 0.007
FCC 106	N	Y	33	-0.05	0.06	-0.060 ± 0.004
FCC 119	Y	Y	85	-0.24	-0.00	0.095 ± 0.010
FCC 136	N	Y	36	-0.14	0.09	-0.057 ± 0.004
FCC 143	N	Y	36	-0.03	0.12	-0.092 ± 0.004
FCC 148	Y	Y	322	-0.11	-0.08	-0.008 ± 0.004
FCC 152	Y	Y	389	-0.13	-0.13	n
FCC 182	N	Y	85	-0.06	0.17	-0.104 ± 0.004
FCC 190	N	Y	44	-0.10	0.11	-0.001 ± 0.005
FCC 202	N	Y	44	-0.19	0.11	-0.005 ± 0.009
FCC 203	N	Y	44	-0.13	0.05	-0.001 ± 0.006
FCC 204	N	Y	37	-0.08	0.07	0.024 ± 0.005
FCC 249	N	Y	36	-0.04	0.07	-0.085 ± 0.005
FCC 255	Y	Y	36	-0.07	-0.03	-0.002 ± 0.002
FCC 277	N	Y	36	-0.03	0.07	-0.074 ± 0.002
FCC 288	Y	Y	41	-0.12	-0.04	-0.017 ± 0.004
FCC 301	N	Y	30	-0.10	0.02	-0.033 ± 0.002
FCC 303	Y	Y	36	-0.15	-0.01	-0.007 ± 0.004
FCC 310	N	Y	36	-0.01	0.04	-0.097 ± 0.004
FCC 324	Y	Y	73	-0.07	0.03	0.028 ± 0.005
FCC 335	Y	Y	70	-0.34	-0.03	-0.074 ± 0.005

Table 3.2 – Table of Fornax dEs color profile parameters:

(1) Name of the galaxy from the Fornax Cluster Catalog. (2) Indicates whether the galaxy is blue (Y) or not (N). A galaxy is blue if its total color is bluer than the CMR. (3) If the center of the galaxy is blue (or not), it is shown by Y (N). A galaxy has a blue core when the color of its central part is bluer than the fitted line to the outer color of the galaxy (shown by $X_{outer\ fit} > 0$ for red and $X_{outer\ fit} < 0$ for blue centers). (4) Size of the blue or red center of each galaxy, separated by the black vertical line with an estimated error of $\sim 20\%$. (5) $\langle Color_{data} - Color_{red\ line} \rangle$: the average excess light in the center of the galaxy from the red fitted line in the color profiles (Formula 3.1). (6) $\langle Color_{data} - Color_{CMR} \rangle$: the average excess light of the galaxy from the CMR line in the color profiles (the green line). (7) Color gradient of each galaxy excluding the red or blue centers. If a galaxy is completely blue without any fitted line, or does not have a blue or red center, this is indicated with ‘n’.

Figure 3.8 – Core size vs. magnitude in the Fornax, Virgo, and Coma clusters. The yellow markers show the change of the core size for FCC301 before and after (marked with an ‘x’ sign) putting it at the distance of Coma. The zero core size could be a nondetectable core or a galaxy without a core.

magnitude relation is used for the Coma cluster, color–magnitude relations table in previous chapter (Table 2.3). Since the two filters which have been used in den Brok et al. (2011) for Coma cluster are F475W and F814W, we used formula 2.3 to transform $(F475W - F814W)$ to $(F475W - F850LP)$, in order to be compatible to the colors in our Fornax and Virgo samples. The core size, excess light from the fitted line and from the CMR, and the color gradient are calculated in the same way as in the Fornax and Virgo clusters to make a similar table for Coma; see Table 3.5 of the Appendix.

3.4.2 Presence of blue centers in the galaxies

Here, we used both the *blue core* and *blue galaxy* definitions as follows: if the core of a galaxy, as separated by the black dashed vertical line, is below the red fitted line in its color profile, it has a *blue core* and when the whole color profile of a galaxy is below the green color–magnitude relation line, it is a *blue*

VCC number (1)	Blue galaxy (2)	Blue core (3)	r_{core} (pc) (4)	$X_{outer\ fit}$ (5)	X_{CMR} (6)	$\nabla(g' - z')$ (7)
VCC 9	Y	Y	21	-0.11	-0.34	-0.024 ± 0.005
VCC 21	Y	Y	34	-0.06	-0.32	0.187 ± 0.010
VCC 33	Y	Y	25	-0.07	-0.44	0.022 ± 0.005
VCC 140	N	Y	21	-0.05	-0.06	-0.008 ± 0.002
VCC 200	N	Y	34	-0.04	0.10	-0.035 ± 0.003
VCC 437	N	Y	34	-0.12	-0.03	0.053 ± 0.006
VCC 543	N	Y	34	-0.03	-0.04	-0.019 ± 0.005
VCC 571	Y	Y	41	-0.20	-0.07	-0.045 ± 0.026
VCC 698	N	Y	80	-0.04	-0.02	-0.037 ± 0.003
VCC 751	N	Y	34	-0.03	0.12	-0.005 ± 0.004
VCC 778	Y	Y	11	-0.03	-0.53	0.032 ± 0.002
VCC 828	Y	N	21	0.10	-0.51	0.047 ± 0.003
VCC 856	N	Y	31	-0.07	-0.03	0.006 ± 0.002
VCC 1025	N	Y	21	-0.02	0.00	-0.123 ± 0.002
VCC 1049	Y	Y	n	n	-0.09	n
VCC 1075	N	Y	28	-0.18	0.07	0.006 ± 0.006
VCC 1087	N	Y	34	-0.04	-0.01	-0.043 ± 0.003
VCC 1125	N	Y	106	-0.02	-0.02	0.002 ± 0.005
VCC 1146	Y	Y	13	-0.09	-0.39	-0.002 ± 0.011
VCC 1178	N	Y	28	-0.07	0.08	-0.030 ± 0.003
VCC 1192	N	Y	49	-0.07	0.28	-0.005 ± 0.006
VCC 1261	Y	Y	21	-0.08	-0.16	-0.010 ± 0.002
VCC 1283	N	Y	21	-0.06	0.04	-0.056 ± 0.003
VCC 1297	N	Y	34	-0.04	0.28	-0.056 ± 0.006
VCC 1303	N	Y	28	-0.09	0.01	-0.102 ± 0.005
VCC 1327	N	N	n	n	-0.15	n
VCC 1355	N	Y	41	-0.17	0.01	-0.044 ± 0.006
VCC 1407	N	Y	41	-0.06	0.07	0.024 ± 0.005
VCC 1422	N	Y	21	-0.07	-0.10	-0.032 ± 0.003
VCC 1431	N	Y	128	-0.07	0.13	-0.058 ± 0.007
VCC 1440	N	Y	28	-0.04	0.09	-0.109 ± 0.003
VCC 1475	N	Y	25	-0.03	-0.04	-0.046 ± 0.003
VCC 1488	Y	Y	n	n	-0.26	n
VCC 1499	Y	Y	n	n	-0.60	n
VCC 1528	N	Y	34	-0.05	0.08	-0.033 ± 0.003
VCC 1537	Y	Y	21	-0.04	-0.53	0.035 ± 0.004

Table 3.3 – Table of Virgo dE color profile parameters. For the definition of the columns, see Table 3.2

VCC number	Blue galaxy	Blue core	r_{core} (pc)	$X_{outer\ fit}$	X_{CMR}	$\nabla(g' - z')$
(1)	(2)	(3)	(4)	(5)	(6)	(7)
VCC 1539	N	n	n	n	0.05	0.113 ± 0.005
VCC 1545	N	Y	34	-0.04	0.16	-0.121 ± 0.005
VCC 1627	N	Y	28	-0.04	0.29	-0.068 ± 0.002
VCC 1630	Y	Y	21	-0.15	-0.57	0.079 ± 0.008
VCC 1661	N	Y	54	-0.12	0.06	0.062 ± 0.006
VCC 1695	Y	N	19	0.05	-0.13	0.030 ± 0.003
VCC 1779	Y	Y	n	n	-0.22	n
VCC 1828	N	Y	49	-0.08	0.10	-0.041 ± 0.006
VCC 1833	Y	n	n	n	-0.02	0.047 ± 0.001
VCC 1857	Y	n	n	n	-0.20	-0.001 ± 0.003
VCC 1861	N	Y	66	-0.10	0.06	-0.005 ± 0.006
VCC 1871	N	Y	28	-0.09	0.19	-0.040 ± 0.002
VCC 1895	Y	Y	21	-0.03	-0.02	0.015 ± 0.003
VCC 1910	N	Y	34	-0.13	0.14	0.017 ± 0.004
VCC 1913	N	Y	34	-0.04	0.02	-0.104 ± 0.003
VCC 2019	N	Y	34	-0.07	-0.02	-0.026 ± 0.004
VCC 2048	Y	Y	23	-0.03	-0.09	0.002 ± 0.003
VCC 2050	N	n	n	n	0.10	-0.035 ± 0.004

Table 3.4 – Table 3.3 continued

galaxy. The definition of a blue center in Pak et al. (2014) and Lisker et al. (2007) could be a blue galaxy or just a blue center in our study, since they do not separate the center as we do. In Figure 3.2, all galaxies with a fitted line have a blue core, sometimes a very small one, however they are not necessarily blue galaxies. These blue centers are confirmed by aperture photometry and for some of them it is clear in their color and unsharp masked images.

As can be found in the color profiles and the table of the galaxies in Virgo, there are two galaxies with a red center: VCC828 and VCC1695. They most likely have a dusty center or as Ferrarese et al. (2006) mentioned for VCC1695, the spiral structure and dust is visible in their color images. There are some completely blue galaxies for which we did not fit a line, as in the Fornax sample: VCC1049, VCC1488, VCC1499, and VCC1779, and some galaxies that do not have any distinct and distinguishable center: VCC1539, VCC1833, VCC1857, and VCC2050. Apart from the mentioned galaxies, and VCC1327 to which we did not fit a line, 43 out of 54 other galaxies have a blue center. Studying color profiles with SDSS data, Lisker et al. (2006) classified VCC21, VCC1779, VCC1488, and VCC1499 as dEs with blue centers which are also very blue

Figure 3.9 – Simulation of the color profile of FCC301 at the distance of Coma in red, together with its original color profile in blue.

ones in our color profiles of the Virgo galaxies.

In our sample of the Coma cluster, 19 galaxies do not have any detectable core ($\sim 47\% \pm 3\%$). It could be that because of the distance to Coma a small core exists but it is not detectable, or that these galaxies do not have a core at all. There are no galaxies with a red core in our Coma sample. Finally, 29 out of 42 dEs have a blue center in our sample for this cluster.

3.4.3 Comparison between the clusters

The three clusters that are used in this study, Fornax, Virgo, and Coma, have distinct characteristics. Comparing Fornax and Virgo with the Coma cluster, one should keep in mind that Fornax and Virgo with distances of 16.5 and 20.0 Mpc (Blakeslee et al. 2009), are almost at the same distance when compared to the Coma cluster, which is at 100 Mpc (Carter et al. 2008). To understand how the distance is affecting our parameters in Coma, we simulated the impact of distance on the Fornax and Virgo images, that is, the effect of putting a galaxy from Fornax or Virgo at the distance of Coma. As an example we chose one galaxy from the Fornax sample: FCC301. This galaxy is convolved with a Gaussian function to see the effect of distance on our method to determine the blue center. The core size of the galaxy is not detectable at the distance of the Coma cluster; see Figure 3.9. One should take this into account when

Figure 3.10 – Excess from the fitted red line ($X_{outer\ fit}$) vs. magnitude in the Fornax, Virgo, and Coma clusters. As the yellow makers show for FCC301, the excess light drops to zero after putting it at the distance of Coma (the one at the distance of Coma has a ‘x’ symbol on it). A negative (positive) excess is driven by a bluer (redder) center than the galaxy.

comparing the Coma cluster with Fornax and Virgo. We show more results of this convolution in the following figures.

To see the effect of the cluster environment on the calculated parameters, we compared these parameters in the three clusters in Figs. 3.8, 3.10, 3.11, and 3.12. Here is the description of each plot:

(A) Figure 3.8 shows the size of the blue or red core region in parsec vs. the magnitude of its galaxy and its histogram for the three clusters. The estimated errors of the center sizes are about 20%. A distance of 50 pc corresponds to about 11, 12, and 2 pixels at the distance of Fornax, Virgo, and Coma, respectively. For Fornax and Virgo, most galaxies have a core size between 0 and 50 pc whereas the core sizes in the Coma cluster peak at values between 50 and 100 pc. The yellow diamonds are FCC 301 at its true distance and when simulated to be at the distance of the Coma cluster (marked with an ‘x’

symbol). The core size of the galaxy is smaller at the distance of Coma, and becomes smaller than 50 pc (see Figure 3.9). The larger size of the cores in Coma has been noted before (den Brok et al. 2014), although that study noted that it was not clear if this size difference was due to the quality of the data, incomplete knowledge of the PSF, or actual physical differences. We note that the galaxies located at $y=0$, the dotted line, are either a galaxy with a small nondetectable core or a galaxy without any specific core. No special trend is obvious in this plot. The galaxies that have very large cores are those with extended blue regions.

(B) Figure 3.10 shows the equation used to calculate the excess light, $X_{outerfit}$, which is explained in Formula 3.1. The sign of the excess light from the fitted line to the outer part is an indication of the color of the center; a positive sign refers to a red core and a negative one shows a blue core. Most of the galaxies have a negative excess light as a result of their blue core. This plot shows that there is no galaxy with a red center in the Fornax and Coma clusters. In Virgo, there are two galaxies with a red core: VCC828 and VCC1695. The peak of excess light from the fitted line in all of these three clusters is in the range of -0.05 to 0. The excess light of FCC301 becomes zero after moving it to the distance of Coma, as yellow markers show, which is a predictable result due to the distance of this latter cluster. This could explain the smaller excess light of the galaxies in the Coma sample in the same range of magnitude, as the difference between the color of the core and the rest of the galaxy is less distinguishable. In general we see a trend from fainter galaxies with larger and bluer cores to brighter ones with smaller and less blue cores. This result is compatible with Turner et al. (2012) who noted that redder nuclei reside in more luminous hosts in the Fornax cluster and also that most of the cores are bluer than their host galaxies. The galaxies with very large excess are always extended, which is clear in their color profiles in Figure 3.2.

(C) The plot in Figure 3.11 is the excess light from the CMR, X_{CMR} , of each galaxy versus its magnitude in g' -band. It is comparable to Figs. 2.5 and 2.6, although here we can better study the distribution of the galaxies regarding the CMR of each cluster. The Coma sample is more concentrated around zero and has galaxies on both sides. In comparison, Virgo is more diffuse with both redder and bluer galaxies compared to the CMR. We emphasize here that the positive and negative signs represent the red and blue color of the total profile and not just the core. In this plot, very red galaxies are mostly compact ellipticals and very blue ones are star-forming galaxies as discussed in Section 2.4.1. It is important to note that the excess light value after convolution of FCC 301 is unchanged, and so the comparison of the clusters is more reliable in this parameter. It is remarkable that galaxies that are brighter than $M_{g'} = -17.5$ are more concentrated around the CMRs. No clear trend is visible in this plot.

Figure 3.11 – Excess light from the CMR line vs. magnitude in the Fornax, Virgo, and Coma clusters. The yellow point with an ‘x’ symbol on it shows FCC301 before and after it was simulated to be at the distance of Coma. X_{CMR} does not change after convolution. The extreme negative points are galaxies with young stellar populations and the most positive ones are dusty galaxies.

(D) In Figure 3.12, the color gradients of Fornax, Virgo, and Coma are plotted. Here the yellow markers show the change from before to after convolution for FCC301. The gradients for most galaxies are negative, although for the faintest galaxies many are also positive. Since the young centers have been removed here, this figure shows just the old stellar populations in the outer part of the galaxies. Virgo and Fornax have more galaxies with positive color gradient, suggesting that the star-forming regions are more extended than the centers. A trend from negative and brighter galaxies to positive and fainter ones can be distinguished here. The Spearman’s rank correlation coefficient for all the galaxies together in this plot is 0.2, which shows a weak correlation. This coefficient is the highest for Fornax 0.49 and is lower for Virgo and Coma, 0.06 and 0.20.

Figure 3.12 – Color gradient vs. magnitude for the Fornax, Virgo, and Coma clusters. The yellow points show FCC301 before and after (with an ‘x’ symbol on it) simulated at the Coma distance.

3.5 Discussion

In this chapter, we presented the color profiles of dEs in the Fornax and Virgo clusters and we used the color profiles of den Brok et al. (2011) for the Coma cluster. These clusters were observed using ACS on HST, giving us an opportunity to study the color of the innermost parts of the dEs, which is almost impossible from the ground. We parameterized these radial color profiles to study their differences in the three clusters and to find out how the cluster environment can possibly affect them.

The most important result of this paper is the large fraction of dEs with young stellar populations in their centers. As discussed in Section 3.4.2, the number of blue-cored dEs changes from cluster to cluster. In Fornax, all the galaxies in our magnitude range have a bluer center than their host galaxies. In Virgo, about $85\% \pm 2\%$ have a bluer center. In the Coma Cluster, a minimum of $53\% \pm 3\%$ of the sample have a clear blue core. This is a lower limit for

Coma cluster due to its distance, as explained in Section 3.4.3. Some of these galaxies contain a considerable amount of gas which has not been blown away. For example, Zabel et al. (2019) reported the detection of molecular CO in FCC335 and FCC90. The galaxies that have a straight color profile, that is, no core, could be galaxies with a small non-detectable core or a galaxy without any bluer or redder center (mostly found in the Coma cluster; see Figure 3.9).

For all three clusters, most galaxies have an excess light from the fitted line, $X_{outerfit}$, in the interval $[-0.05, 0]$, as can be seen in Figure 3.10. There are just a few galaxies with redder centers in the Virgo cluster and none in the other two clusters. We showed that the bluest cores are found in fainter galaxies. This result is compatible with the previous studies on the nuclei of dEs, except in those previous studies no distinction was made between the core, that is, the blue region, and the nucleus, the region with an enhanced surface brightness profile. Lotz, Miller & Ferguson (2004), for the Leo Group, Fornax, and Virgo clusters ($-12 < M_B < -18$), showed that the nuclei of dEs are bluer than their residing galaxies, $\delta(V - I) = 0.1 - 0.15$ mag, and that redder and brighter dEs have redder nuclei. These latter authors failed to find any correlation between nuclear properties such as magnitude and color and projected distance of the galaxy from the center. We also did not find any trend between the excess light from the fitted line and the projected distance of each galaxy to the cluster center.

Several studies have reported blue-cored early-type galaxies in various environments, associating them with recent star-formation in these areas. Beside their blue cores, the young stellar populations were confirmed using different tools such as $H\alpha$ emission and UV flux. Pak et al. (2014) studied a sample of 166 galaxies in the Ursa Major cluster located at 17.4 Mpc (Tully & Courtois 2012, ;between those of Virgo and Fornax) with ground-based SDSS Data and data from the GALEX satellite. The sample of this latter study was chosen in the magnitude range of $-21.5 < M_r < -13.5$. In this range, 16 galaxies out of 23 dEs, that is $\sim 70\%$, showed a blue core based on their radial NUV-r color profiles. Pak et al. (2014) claimed that since the UV flux is particularly sensitive to the presence of young stars (< 1 Gyr), the blue UV-optical colors of the blue-cored early-type dwarfs indicate that these galaxies have experienced recent or ongoing star formation activity in their central regions. To confirm the recent star formation, the authors looked at the $H\alpha$ emission of these galaxies, which is a good indicator of O- and B-type stars with an age of less than a few million years (Kennicutt 1998). They reported that about 75% of them have $H\alpha$ emission with equivalent width of more than $2\text{\AA}$.

In the Fornax cluster, De Rijcke, Buyle & Koleva (2013) identified an offset blue core in FCC46, with $H\alpha$ and H I emission indicating ongoing star formation.

Lisker et al. (2006) sample the galaxies that overlap with this paper in the Virgo cluster; we also found blue cores in these galaxies (Section 3.4.2). The difference between the fractions of galaxies with blue cores is purely caused by a difference in resolution, and the fact that the PSF of HST is so well known. Similar studies have confirmed ongoing star formation by H_α imaging (Boselli et al. 2008).

Size of the blue cores and comparison to nuclear clusters

Our method to find the blue or red cores in this paper is different from what has been used to detect the nuclei of early-type galaxies in HST studies of Fornax, Virgo, and Coma (Turner et al. 2012; Côté et al. 2006; Lotz, Miller & Ferguson 2004; den Brok et al. 2014). Their detected nuclei are the excess light in the center of the galaxy when fitting a Sérsic function to the surface-brightness profile. Here, on the other hand, we used the color contrast to define the inner blue regions. The effective radii of the nuclei, determined from the surface-brightness profiles, are normally much smaller than our blue cores, indicating that they are not measuring the same thing.

Figure 3.13 shows the measured core size of the early-type galaxies in this paper versus the effective radii of the nuclei of the same galaxies from Côté et al. (2006) (Virgo) and Turner et al. (2012) (Fornax). As is seen in this image, our blue cores are generally larger than the nuclei. The two exceptions in Virgo, which have much larger nuclei than blue core radii, are VCC1630 and VCC1913. Galaxies without a detectable core or nucleus are shown as upper limits on the $x=0$ or $y=0$ lines. Although the nuclear clusters do not correspond one-to-one with the blue core regions, several studies have shown that the nuclear clusters are for the most part bluer than their host galaxies (Côté et al. 2004; Turner et al. 2012; den Brok et al. 2014). These studies also noted a (weak) correlation between the color of the nucleus and the luminosity of its galaxy, finding bluer nuclei to reside in fainter galaxies. This is comparable to the trend that we discussed in Fig 3.10; fainter dEs on average show a larger blue excess.

We found that the size of the blue/red core of the galaxy does not correlate with the luminosity of the host galaxy; Figure 3.8. Apart from the fact that the fraction of galaxies with blue or red cores differs from cluster to cluster, the properties of the cores vary so much from cluster to cluster that no general trends are seen. The only clear conclusion here is that no large core radii (> 300 pc) are seen in the Coma cluster.

Figure 3.13 – Effective radii of the nuclei in the *g*-band vs. the radii of the cores of the dEs in Fornax and Virgo. The effective radii of the nuclei in Fornax were taken from Turner et al. (2012) and the ones in Virgo were taken from Côté et al. (2006). The core sizes are tabulated in Tables 3.2 and 3.3.

3.5.1 Comparison between the clusters and possible formation scenarios

In this paper, we studied three clusters with distinct characteristics. Comparing the environment of clusters, Coma is a relaxed, dense, and rich cluster at a distance of 100 Mpc (Carter et al. 2008). It is about a factor ten more massive than the Virgo cluster. Fornax, at a distance of 20 Mpc, is six times less massive, and is more regular in shape with a shallower potential well compared to Virgo (Jordán et al. 2007a, ;see Table 3.1).

To study the effects of the cluster environment on the formation of galaxies, we used dwarf ellipticals as test objects, since their shallow gravitational potential causes them to interact more effectively with their environment. The most important external processes that can work here are ram pressure stripping (RPS) (Gunn & Gott 1972) and harassment (Moore et al. 1996). These can remove the ISM of the galaxy, quench the star formation, and in the meantime

even re-ignite the central star formation activity (Kronberger et al. 2008).

For the external factors that can affect dEs, Urich et al. (2017) discussed harassment and ram pressure stripping in the context of the formation of blue-cored dEs. These latter authors suggested that galaxy harassment is less effective in clusters like Virgo, given their large velocity dispersion, and more efficient in group environments (Yozin & Bekki 2015). Urich et al. (2017) claimed that the ram pressure stripping is therefore more likely to explain their blue-core dEs in the Virgo cluster. According to the model of Vollmer (2009), ram pressure stripping has a hard time in removing the gas from the center of the galaxies and it can even raise the star formation rate in the cores (Kronberger et al. 2008).

We found that the fraction of blue galaxies with blue cores, is smaller in Coma than in Virgo and Fornax. Interestingly, Fornax does not seem to be very different here from Virgo, except that its CMR is slightly bluer than that of Virgo. If Coma has fewer blue outliers than Virgo, and fewer and smaller blue-core regions, then Virgo should have fewer blue outliers than Fornax. Since this is not the case, we probably have to look at the differences in the internal structures of Virgo and Fornax. The galaxy number density in the center of Fornax is twice as high as in the Virgo cluster (Jordán et al. 2007b), while the velocity dispersion in the Virgo cluster is two times higher ($\sim 760 \text{ km s}^{-1}$) than in Fornax, making the harassment timescales in the Virgo cluster four times longer than in the Fornax cluster (Venhola et al. 2018). On the other hand, the density of the X-ray gas in the center of Virgo (Simionescu et al. 2017) is roughly five times higher than in the Fornax cluster (Paolillo et al. 2002), which combined with the two-times-higher velocities of the Virgo dwarfs makes the ram-pressure in the Virgo cluster approximately 20 times higher than in the Fornax cluster. To this we have to add that in Fornax the ratio of ellipticals to spirals is larger than in Virgo (Ferguson & Sandage 1988). Virgo is an active and irregular cluster with a young dynamical nature (Boselli et al. 2014; Mei et al. 2007; Binggeli, Popescu & Tammann 1993; Drinkwater et al. 2001; Conselice, Gallagher & Wyse 2001). Sybilska et al. (2017) showed that Virgo has a nonsymmetric density distribution by studying the number density map of the cluster.

Hence, with harassment being more effective in the central regions of Fornax and ram pressure stripping being more effective in Virgo, the effects seem to more or less cancel each other out. However, one thing is very different in these clusters: the fraction of red outliers of the CMR. Since the compact ellipticals that cause this are often caused by galaxy harassment or interactions, our observational result could indeed mean that harassment is much stronger in Virgo, meaning that bright nuclear dwarfs have a much higher probability of

losing their outer parts. It would also mean that we expect more compact ellipticals in Coma; however, this is not the case since the cluster is much more relaxed now, and such objects are indistinguishable from stars with HST at this moment. Detailed simulations are needed to show whether this hypothesis is true, as well as observations covering a larger magnitude range to make stronger predictions.

We must also note that our sample of dEs in Coma used in this study is mostly from the central region of the cluster as the ACS camera failed during the later stages of the survey. Studies show that the color of a galaxy correlates with the density of its environment; redder galaxies reside in denser environments (Gavazzi et al. 2013; Boselli & Gavazzi 2014). Since the galaxies in the center of the cluster have entered the environment earlier and have gone through more environmental influences, they have less star formation (Sybilska et al. 2017; Lisker et al. 2013). This could well be the reason behind fewer blue outliers in Coma in Figure 2.5.

Investigating the formation of dEs with a blue core, transition-type dwarf galaxies (TTDs) can be important. De Looze et al. (2013) chose their sample of 36 TTDs based on SDSS spectra of the Virgo cluster. From this sample, 13 of them were detected by the Herschel Space Observatory (Pilbratt et al. 2010) of which three galaxies are in common with our sample: VCC571, VCC1488, and VCC1499. The galaxy VCC571 has H_α absorption which is a sign of young stellar populations, and VCC1488 and VCC1499 have strong H_α absorption which shows relatively young ($\sim 1\text{Gyr}$) stellar populations without current star formation, probably indicating a rapid truncation of the star formation activity. Transition-type dwarf galaxies are spiral galaxies losing their gas entering the cluster environment and turning to quiescent dEs (Boselli et al. 2008; Lisker et al. 2006). In this process they can have properties of both early- and late-type galaxies. They claimed that several TTDs have blue central regions, which is a hint of outside-in gas removal. Regarding the blue-cored TTDs, these latter authors suggested that some of the dEs should be formed by infalling of the late-type galaxies in the field to the cluster and their transformation to early-type galaxies. The authors concluded that interaction with the cluster environment, especially through ram pressure stripping, is guiding the evolution of these TTD.

What do these new results tell us about the formation of nuclear clusters? Turner et al. (2012); Côté et al. (2004) studied the nuclei of the dEs, taking advantage of the high resolution of HST. They analyzed the parameters of the nuclei and their projected distances from the cluster center and found similar results to ours; they did not find any evidence that their properties depend on galaxy cluster distance. In addition, the similarities between the nuclei of

the early-type galaxies in our three clusters with distinct properties lead the authors to the conclusion that the environment of the clusters does not have a crucial effect on their formation and evolution. Considering these results, one may conclude that the formation of nuclei in dEs is mainly determined by internal and local factors. There are two main possible scenarios for their formation: infall of globular clusters or infall of gas to the center of the galaxy. Considering the former, globular clusters around the core experience dynamical friction, merge, and spiral to the center. This is not a new idea; Tremaine, Ostriker & Spitzer (1975) suggested that the nucleus of M31 formed in the same way. This process leads to a lack of or less globular cluster around the center (Capuzzo-Dolcetta & Tesseri 1999). Calculating the timescale of dynamical friction in numerical simulations, Turner et al. (2012) concluded that the nuclei of the galaxies in the range of low to intermediate mass can be formed by this mechanism and that it is appropriate for forming the nuclei of nonmassive galaxies in their Virgo and Fornax samples (see more in e.g. Lotz et al. 2001; Milosavljević 2004).

The latter possible scenario that can form the nuclei is gas accretion into the center, which causes star formation in the core of the galaxy (van den Bergh 1986). There are some theories explaining how gas is transported to the inner parts of the galaxy (Milosavljević 2004; Mihos & Hernquist 1994; Hopkins & Quataert 2011). Bekki, Couch & Shioya (2006) and Bekki (2007) with chemodynamic simulations of the inner 1 kpc of dwarf galaxies showed that nuclei are younger and more metal rich than their hosts. Since feedback is more effective in low-mass galaxies, the time that gas needs to settle in the center increases for fainter galaxies. This leads to the bluer and younger nuclei in low-mass galaxies.

3.6 Conclusion

We conclude by stating the main results of this paper:

- The most important result is the large number of blue-cored dEs in all three clusters: all galaxies in the Fornax cluster sample, $85\% \pm 2\%$ of the Virgo sample, and a lower limit of $53\% \pm 3\%$ in the Coma cluster sample, which is discussed in detail in Section 3.4.2. Considering the very distinct characteristics of these clusters and the distribution of these galaxies in each cluster, their formation and evolution are influenced by different factors and cannot be explained by a single theory. The possible scenarios are presented in Section 3.5.1.
- A trend that brighter galaxies generally have negative color gradients, which become less negative and even positive for our faintest galaxies, can be found in the color gradients of all three clusters.

- The bluest cores are found in the faintest galaxies. There is no obvious correlation between the sizes of the blue cores and the luminosity of their host galaxies in any of the clusters.

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Appendix

3

3.A Color profiles of Virgo and table of Coma

Figure 3.14 – Color profile of Virgo early-type dwarf galaxies

Figure 3.15 – Fig 3.14 continued.

Figure 3.16 – Fig 3.14 continued.

Figure 3.17 – Fig 3.14 continued.

Figure 3.18 – Fig 3.14 continued.

Figure 3.19 – Fig 3.14 continued.

Figure 3.20 – Fig 3.14 continued.

Coma ID	r_{core} (pc)	$X_{OuterFit}$	X_{CMR}	$\nabla(g' - z')$
(1)	(2)	(3)	(4)	(5)
COMAi13030.949p28630.18	125	-0.04	-0.00	-0.068 $\pm$ 0.003
COMAi13024.823p275535.89	94	-0.04	-0.01	-0.052 $\pm$ 0.003
COMAi13018.782p275613.47	222	-0.02	-0.13	-0.097 $\pm$ 0.003
COMAi13021.672p275354.80	78	-0.02	-0.03	-0.060 $\pm$ 0.002
COMAi125930.268p28115.17	71	-0.04	0.06	-0.056 $\pm$ 0.005
COMAi125937.988p28003.56	78	-0.04	-0.07	-0.094 $\pm$ 0.002
COMAi125820.533p272546.3	86	-0.02	-0.18	-0.072 $\pm$ 0.011
COMAi125815.275p272752.96	94	-0.08	0.09	-0.053 $\pm$ 0.006
COMAi125704.336p273133.26	138	-0.02	-0.01	-0.027 $\pm$ 0.004
COMAi13035.418p275634.5	94	-0.03	-0.07	-0.058 $\pm$ 0.002
COMAi125845.544p274513.68	125	-0.05	-0.01	-0.048 $\pm$ 0.004
COMAi13041.192p28242.38	71	-0.02	0.03	-0.057 $\pm$ 0.003
COMAi13018.543p28549.48	94	-0.04	0.03	-0.001 $\pm$ 0.006
COMAi13005.403p28128.24	167	-0.02	-0.13	-0.081 $\pm$ 0.003
COMAi125950.181p275445.54	125	-0.04	0.03	-0.047 $\pm$ 0.003
COMAi125942.306p275529.11	167	-0.06	-0.03	-0.175 $\pm$ 0.005
COMAi125926.459p275124.76	71	-0.03	0.02	-0.035 $\pm$ 0.003
COMAi125948.590p275858.1	71	-0.03	-0.20	-0.022 $\pm$ 0.006
COMAi125953.930p275813.76	104	-0.04	0.05	-0.008 $\pm$ 0.004
COMAi125946.941p275930.84	78	-0.02	-0.06	-0.040 $\pm$ 0.005
COMAi13026.152p28032.2	167	-0.06	-0.01	-0.042 $\pm$ 0.008
COMAi13044.634p28602.30	n	n	-0.05	-0.039 $\pm$ 0.002
COMAi125904.792p28301.21	n	n	-0.03	-0.032 $\pm$ 0.002
COMAi125909.465p28227.38	n	n	0.05	-0.053 $\pm$ 0.004

Table 3.5 – Table of Coma dEs color profile paramters: (1) Coma ID. (2) The size of the blue or red center of each galaxy, separated by the black vertical line with an estimated error of $\sim 20\%$ (3) $< Color_{data} - Color_{red\ line} >$: the average excess light in the center of the galaxy from the red fitted line in the colour profiles (4) $< Color_{data} - Color_{CMR} >$: the average excess light of the galaxy from the CMR line in the colour profiles (the green line) (5) Color gradient of each galaxy excluding the red or blue centers. Whether a galaxy is totally blue without any fitted line or it appears to not having a bluer or red center, the undefinable parameters are shown by ‘n’.

Coma ID	r_{core} (pc)	$X_{OuterFit}$	X_{CMR}	$\nabla(g' - z')$
(1)	(2)	(3)	(4)	(5)
COMAi125911.545p28033.38	n	n	0.11	-0.060 ± 0.011
COMAi125940.278p275805.73	n	n	0.06	-0.015 ± 0.005
COMAi125939.657p275713.86	n	n	0.00	-0.026 ± 0.002
COMAi125931.115p275717.73	n	n	0.11	0.039 ± 0.001
COMAi13034.427p275604.97	n	n	0.00	0.014 ± 0.002
COMAi125937.10p28106.95	n	n	0.07	-0.008 ± 0.001
COMAi13011.143p28354.92	n	n	-0.01	-0.083 ± 0.002
COMAi125935.286p275149.16	n	n	0.01	-0.021 ± 0.002
COMAi125959.476p275626.4	n	n	-0.06	-0.019 ± 0.003
COMAi13005.684p275535.20	n	n	-0.22	0.072 ± 0.002
COMAi125944.182p275730.39	n	n	-0.05	-0.026 ± 0.003
COMAi13006.399p28015.86	n	n	-0.03	-0.046 ± 0.006
COMAi125944.217p275730.29	n	n	-0.06	-0.038 ± 0.003
COMAi13017.643p275915.26	n	n	0.04	-0.025 ± 0.003
COMAi13018.873p28033.38	n	n	0.08	-0.022 ± 0.005
COMAi13007.123p275551.49	n	n	-0.00	-0.081 ± 0.007

Table 3.6 – Table 3.5 continued

Figure 3.21 – Colour profile of Virgo early-type dwarf galaxies

Figure 3.22 – Figure 3.21 continued

Figure 3.23 – Figure 3.21 continued

Figure 3.24 – Figure 3.21 continued

Figure 3.25 – Core size vs. magnitude in the Fornax, Virgo, and Coma clusters. The yellow markers show the change of the core size for FCC301 before and after (marked with an ‘x’ sign) putting it at the distance of Coma. The zero core size could be a nondetectable core or a galaxy without a core.

3.B Larger Coma sample

In this chapter we used a small sample of early-type galaxies in the Coma cluster. Here we discuss the whole sample from den Brok et al. (2011) which contains 121 galaxies. We present the plots which are comparing the three clusters with a larger sample of Coma, similar to Figure 3.8 to 3.12. In Figure 3.25 to 3.28, There are two symbols for the Coma cluster. The green one is for the galaxies in the same magnitude range as Fornax and Virgo and the gray one is showing larger sample. The color profiles of this larger sample excluding the one in Figure 3.21 are shown in Figure 3.29 to 3.37.

Figure 3.26 – Excess from the fitted red line ($X_{outer\ fit}$) vs. magnitude in the Fornax, Virgo, and Coma clusters. As the yellow markers show for FCC301, the excess light drops to zero after putting it at the distance of Coma (the one at the distance of Coma has an ‘x’ symbol on it). A negative (positive) excess is driven by a bluer (redder) center than the galaxy. The very large core sizes are galaxies with extended blue cores.

Figure 3.27 – Excess light from the CMR line vs. magnitude in the Fornax, Virgo, and Coma clusters. The yellow point with an ‘x’ symbol on it shows FCC301 before and after it was simulated to be at the distance of Coma. X_{CMR} does not change after convolution.

Figure 3.28 – Color gradient vs. magnitude for the Fornax, Virgo, and Coma clusters. The yellow points show FCC301 before and after (with an ‘x’ symbol on it) simulated at the Coma distance.

Figure 3.29 – Color profile of the larger sample of Coma

Figure 3.30 – Figure 3.29 continued

Figure 3.31 – Figure 3.29 continued

Figure 3.32 – Figure 3.29 continued

Figure 3.33 – Figure 3.29 continued

Figure 3.34 – Figure 3.29 continued

Figure 3.35 – Figure 3.29 continued

Figure 3.36 – Figure 3.29 continued

Figure 3.37 – *Figure 3.29 continued*

Color distributions of early-type galaxies with CO detection

Abstract

In this chapter, we study the optical properties of the galaxy sample of Zabel et al. (2019), a complete sample of galaxies with CO-detection or upper limits observed with the ALMA in the Fornax cluster. We use the images of our sample from the Fornax Deep Survey (FDS) to investigate the color profiles and color images of these galaxies in the optical bands. Then we focus on dwarf early-type galaxies of this sample and compare them to a control sample of dE galaxies, selected without information about their CO content, in order to study whether the presence of the molecular gas is related to any features distinguishable in the optical. We present the color profiles and color maps in $g - r$ and $u - g$ as well as the residual maps to the elliptical model fits of these galaxies. We find that CO detected galaxies have many distinguishable substructures in their color maps and profiles, mostly at the same place where the CO is found. In contrast, the other dwarf early-types without CO emission appear more regular. Although such visible color substructures like blue young populations and dust in a dwarf early-type can not directly predict any molecular gas, it can be used as a probable hint.

4.1 Introduction

In previous chapters, we used a sample of early-type galaxies in the Fornax cluster and studied their colors, color profiles and color maps. In addition we compared the early-types of Fornax with similar galaxies in the Virgo and Coma clusters. We discussed how the difference in the cluster environment can change the color of a galaxy and make it redder than the red sequence by probably removing its outer gas and stars, making the size smaller than normal galaxies or by re-igniting star formation in an early-type and making it blue. We also showed that the star forming and dusty patches in early-type galaxies can be distinguished using their color and residual maps. We reported that most of the galaxies in our early-type sample had a center that was bluer than the galaxy itself.

In this chapter we will join our studies on star formation in dwarf early-types in previous chapters with the CO detection in the Fornax cluster. The galaxies with CO detection contain gas that can be used to form stars. In this way, we can investigate whether dEs with molecular gas, have any distinguishable features in the optical bands.

The morphology-density relation has shown us that the environment of a galaxy is an important factor in determining its evolution. As an example, galaxy clusters are capable of quenching the star formation of a gas rich galaxy, such as a late-type one and transforming it into a gas-poor early-type. It is shown that the galaxies in clusters have lower fractions of atomic gas when compared to the field (Gavazzi et al. 2005; Solanes et al. 2001; Haynes, Giovanelli & Chincarini 1984).

In general, molecular gas is more tightly bound to the galaxy and is located mostly around the center compared to the atomic gas, which can be affected easier by the cluster environment. Several environmental processes that happen in a cluster can affect galaxies in various ways and transform it. These processes can happen in two ways: in the first method, the environment of a cluster can work as a whole and change the galaxy, e.g., ram pressure stripping (RPS) (Gunn & Gott 1972), viscous stripping (Nulsen 1982), starvation (Larson, Tinsley & Caldwell 1980) and thermal evaporation (Cowie & Songaila 1977). The second type is the interactions between galaxies, such as harassment (Moore et al. 1996) and mergers. Despite early studies, which concluded that the molecular gas of a galaxy can not be removed by the named processes in the cluster (Boselli & Gavazzi 2006; Boselli, Casoli & Lequeux 1995; Stark et al. 1986), recently it is shown that the molecular gas content of galaxies in clusters and groups is lower than of similar ones in the field and molecular gas can be removed by the cluster similar to the atomic gas (Vollmer et al. 2008; Lee et al. 2017; Fumagalli, Zanchetta & Poli 2009). Since the molecular gas

is the direct fuel for forming stars, these environmental effects can change the star formation rate of a galaxy and, eventually cause it to stop.

In galaxies, stars form in giant clouds which consist of molecular hydrogen, H_2 . The abundance of H_2 is quite high whereas considering its low mass, it does not emit any easily detectable lines in giant molecular clouds in quiescent galaxies with typical temperature around 10 K. Only shock-heated H_2 produces some transitions in the NIR. The energies of those correspond to about $T=500$ - 2000 K. Given the hard direct detectability of H_2 , scientists use CO, which is the second most abundant molecule in these clouds. Today, the ground-state rotational transition of carbon monoxide is the most commonly observed tracer molecule of H_2 (Narayanan & Krumholz 2014). The galaxies with CO detection contain gas that can be used to form stars. Since most of the galaxies in the clusters do not have gas, it is likely to presume that galaxies which are detected in CO are in the process of falling into the cluster. Since C and O are considered metals, detection of CO is much more difficult at low metallicities.

In the past, there were some unsuccessful attempted to find CO ($J=1-0$) in ellipticals (Faber & Gallagher 1976), whereas, Wiklind & Rydbeck (1986) were among the first ones who reported detection of CO ($J=1-0$) emission in a dwarf elliptical galaxy, NGC185, using the Onsala Space observatory. They claimed that presence of massive molecular clouds in the center is backing the idea of ongoing star formation by populations of blue stars there. Lees et al. (1991) compared giant ellipticals which have been detected in CO with the undetected ones and noted that the detection rate of the molecular gas in bluer, less luminous ellipticals is more than twice of the bright galaxies.

To investigate the early-type galaxies with molecular gas, Young et al. (2011) used 260 early-type galaxies and did a survey of the volume-limited *ATLAS^{3D}* sample in magnitude range of $21.5 \geq M_{K_s} \geq 26$. They reported that the total detection rate of the early-type galaxies with CO is $56/259 = 0.22 \pm 0.03$. They also found that the detection rate increases, 0.77 ± 0.06 , in galaxies with dusty patches and blue regions, whereas it is only 0.08 ± 0.02 in the ones without those features. The authors concluded that there is a tight correlation between molecular gas content of an early-type galaxy and its dust and young populations substructures.

In order to study molecular gas in the Fornax cluster, Zabel et al. (2019) selected their sample from the galaxies in the Fornax Cluster Catalog (FCC) with stellar mass larger than $3 \times 10^8 M_\odot$ so these galaxies have high enough metallicities to be detected in CO observations. In addition, their sample consists of galaxies with a dust mass of $> 3 \times 10^7 M_\odot$ detected in three or more bands of the Herschel Space Observatory (Pilbratt et al. 2010) with the Herschel Fornax Cluster Survey (Fuller et al. 2014), and of galaxies which had

previous H I detection (based on ATCA data) showing active star formation and therefore the presence of molecular gas. These constraints narrowed their sample to 30 galaxies from different morphological types ranging from giant ellipticals to spirals and dwarfs, spread across the whole cluster. They presented the Atacama Large Millimeter/sub-millimeter Array (ALMA) Fornax Cluster Survey (ALFoCS) which is a complete survey of the Fornax members selected in this way.

Of the Zabel et al. (2019) sample, half of the galaxies were detected in CO. They did not see any trend in their projected distribution onto the cluster for both detected and non-detected ones. Investigating the detected galaxies more, 8 of these galaxies, the ones stellar masses lower than $3 \times 10^9 M_\odot$, show disturbed molecular gas reservoirs, while for the 7 massive galaxies a regular CO-distribution is found. They conclude that the Fornax environment is very active and affects the molecular gas of its members. The reason why the gas in the less massive galaxies is more disturbed is the result of their shallower potential wells, otherwise more massive ones are also undergoing the same interactions from the cluster. They claimed that this detection explains the importance of the cluster environment for even the molecular gas phase, which is tightly bound to the galaxy.

Here, we will use the sample of Zabel et al. (2019) in the Fornax cluster and will see what the optical properties of galaxies with CO are, whether star formation and dust patches are distinguishable and different from ordinary early-type galaxies. We will compare the optical color and residual maps of a galaxy with its CO map to investigate whether we can find any difference between early-types with and without CO detection.

The overview of this chapter is as follows: the description of the sample can be found in Section 4.2. The method that we used to analyze the data is explained in Section 4.3. We present color profiles and color maps of the sample in Section 4.4. We then discuss the results in 4.5 and give some conclusions in Section 4.6.

4.2 Sample Selection and Data

In order to study the relation between star formation and dust, as derived from optical colors, with the molecular gas contents, we selected our sample of galaxies from the sample of Zabel et al. (2019). Their sample selection is explained in the previous section. We used the Fornax Deep Survey (FDS) to investigate the color images of these galaxies in optical bands. The FDS is a new survey of the Fornax cluster which contains 573 galaxies in optical bands using the ESO VLT Survey Telescope (VST). The imaging is done in

the u, g, r and i-bands using the OmegaCAM instrument attached to the VST with a $1^\circ \times 1^\circ$ the field of view and a pixel scale of $0.21''$ per pixel (Venhola et al. 2018). The FDS covers the whole Fornax Cluster, including the Fornax A group.

For most of the galaxies in the sample, 19 galaxies, we used the optical images from Venhola et al. (2018) (FDS) in u, g and r bands to study the $(u - g)$ and $(g - r)$ colors. We chose these bands as $u - g$ shows young populations and $g - r$ represents the dust better (see e.g., Peletier et al. 1999). For bright spirals and lenticulars, 9 galaxies, we used the color profiles and color maps extracted by Iodice et al. (2019) (3 galaxies: FCC167, FCC177 and FCC184) and Raj et al. (2019) (6 galaxies: FCC121, FCC179, FCC285, FCC290, FCC308 and FCC 312), who also used the FDS images. The distance used to the Fornax cluster in this study is 20.0 Mpc ($\mu = 31.51$ mag) (Blakeslee et al. 2009).

There are two galaxies in Zabel et al. (2019) sample for which there are no images available in the FDS: FCC32 and FCC316. Since they are located at the edge of the Fornax cluster, they have not been included in the FDS. Other surveys do not have a clear image with sufficient resolution of these galaxies as well so we decided not to consider them in this study. Since they have not been detected in CO in Zabel et al. (2019), it will not change the result of this study.

4.3 Analysis

To find the color profiles of the 19 galaxies of our sample, we used the FDS images in u, g and r bands. The physical parameters of these galaxies are described in Venhola et al. (2018). We used the cropped images of each galaxy using a field extending to 10 semi-major axes. Venhola et al. (2018) calibrated the images for their exposure times and zero points and they subtracted global sky values. The photometric errors related to the zero-point calibration of the data are 0.04, 0.03, 0.03 mag in u, g, and r respectively (Venhola et al. 2018). Since the color of the center of a galaxy is very sensitive to its PSF, to find the color, first we convolved the image of the galaxy in each band with the PSF of the other band (cross convolution) before running Galphot (Franx, Illingworth & Heckman 1989; Jorgensen, Franx & Kjaergaard 1992) as explained in Chapter 3. The PSFs are from Venhola et al. (2018) and vary from field to field. Their PSF model consists of the inner ($\lesssim 10$ arcsec) and the outer ($\gtrsim 8$ arcsec) parts. The turbulence and scattering of the atmosphere which change all along the observations make the inner PSF. They used the brightest non-saturated stars to model the inner PSF. For the outer PSF, the scatter of the light from the optical surfaces is the most important factor which is calculated using the saturated stars (For more information about PSFs see

Venhola et al. 2018).

After masking the background and foreground objects, we first modeled the galaxy in the g and r filters with an initial run of Galphot on the inner isophotes with varying parameters such as the center, ellipticity and position angle as a function of radius. Then we did the second run for each band by fixing these variables to the output values of the first run in the g band. The final output is the surface brightness profile of each galaxy in each band. In this way, using the magnitudes in g and r filters, the $g - r$ color profiles are calculated. We used similar processes to find the $u - g$ color profiles as well. The colors are in the AB-magnitude system. For a more accurate sky for most of the galaxies we slightly adjusted the sky value, requiring the radial intensity growth curve to converge to a finite value. In addition to color profiles, the g , r and u -bands images are used to make the $g - r$ and $u - g$ color maps.

For the galaxies which are available in Iodice et al. (2019) and Raj et al. (2019), we took their $g - r$ and $u - g$ color profiles, which were obtained in very similar ways. For the color maps, we used the $g - i$ maps from those papers.

4.4 Color Profiles and Color Maps

The color profiles which are made in the way explained above in the $g - r$ and $u - g$ colors are presented in Figure 4.11 to 4.28 in the Appendix. Here, the radius (r) is the circularized distance of each fitted ellipse by Galphot, $r = \sqrt{ab}$, where a and b are semi-major and semi-minor axes of the ellipse. We started our color profiles at 1 pixel equal to $0.21''$ and continued in radius to three effective radii for both $g - r$ and $u - g$. We used the effective radii in r -band presented in (Venhola et al. 2018) from their Galfit models, which are showed by green vertical lines in color profiles. The green horizontal lines in the color profiles are the color of a galaxy with the same magnitude, but on the red sequence. The red sequence color is derived from Roediger et al. (2017). We did not fit a color- $\log(r)$ line to the color profile in the outer parts of the galaxy and did not define the core size like in the previous chapter since, with all various morphological types, they will not be well-defined.

To show the substructures better, we made the $g - r$ and $u - g$ color maps (See Figures 4.11 to 4.28 in the Appendix). Using the color images we can visually see the difference between the images of the galaxy in the two bands, which means that we can see dust patches, regions of bluer, i.e., younger stars, etc. The color in the color maps are scaled to regarding their color profiles. For a more complete overview of the substructures, we also showed the residual image of the galaxy from our Galphot model beside the color maps. In addition the g -band image of each galaxy is shown with scaled colors.

FCC number	M_g (mag)	$u - g$ (mag)	$g - r$ (mag)	Morphology	Detection
(1)	(2)	(3)	(4)	(5)	(6)
44	-14.00	0.45	0.28	dS0	FIR
67	-18.96	0.46	0.28	Sc(edge-on)[e]	FIR, H I, CO
90	-16.96	0.77	0.42	E4 [l]	FIR, H I, CO
102	-15.21	0.73	0.39	ImIV	H I
113	-16.52	0.85	0.48	ScdIII pec	FIR, H I
115	-14.98	0.85	0.48	Sdm(edge-on)	H I
117	-13.32	0.07	0.67	dE0	FIR
120	-15.19	0.95	0.37	ImIV	H I
121	-22.18	1.32	0.54	SBbc(s)I	FIR, H I, CO
167	-21.65	1.84	0.59	S0/a	FIR, CO
177	-18.99	1.36	0.72	S0	FIR
179	-20.07	1.73	0.76	Sa	FIR, CO
184	-20.75	1.88	0.76	SB0	FIR, CO
198	-13.81	1.02	0.64	dE5	FIR
206	-16.06	1.35	0.66	dE0pec	FIR
207	-15.97	1.22	0.66	dE2,N	FIR, CO
235	-18.19	0.95	0.34	ImIII	FIR, H I
261	-15.88	0.87	0.59	dE3,N/ ImIV [e]	FIR, CO
263	-17.72	0.98	0.48	SBcdII	FIR, H I, CO
282	-17.00	1.21	0.66	ImIV/dEpec [e(s)]	FIR, CO
285	-18.36	1.42	0.13	SdIII	FIR, H I
290	-20.11	1.20	0.32	ScII	FIR, H I, CO
302	-15.85	0.75	0.16	Sdm(edge-on)	H I
306	-15.54	0.78	0.32	SBmIII	FIR, H I
308	-18.64	1.49	0.33	Sd(edge-on)	FIR, H I, CO
312	-20.11	1.98	0.51	Scd(edge-on)	FIR, H I, CO
332	-16.08	1.29	0.73	E or S0	FIR, CO
335	-17.30	1.39	0.69	E	FIR, CO

Table 4.1 – Table of the parameters of the sample: (1) Name of the galaxy from the Fornax Cluster Catalog (FCC), (2) the g -band total apparent magnitude from the Sérsic fit, from Venhola et al. (2018), (3) the $(u - g)$ color within one effective radius from Venhola et al. (2018), (4) the $(g - r)$ color within one effective radius from Venhola et al. (2018), (5) the morphological type of the galaxy from Ferguson (1989) (we showed Venhola et al. (2018) morphology, when it is different, which is written in bracket; e : smooth early-type, e(s) : early-type with structure, l: late-type), (6) detection in H I, FIR or CO (Zabel et al. 2019, and references there in). For the galaxies that we took from Iodice et al. (2019) and Raj et al. (2019), we listed the magnitudes in the g -band and the total average $(g - r)$ and $(u - g)$ colors from their tables. The estimated error of the magnitudes are between 0.1 and 0.01.

For the galaxies from Iodice et al. (2019) and Raj et al. (2019), we made similar color profiles, and showed them in Figures 4.29 to 4.33. To be consistent with the above sample, we used the u , g and r profiles of Iodice et al. (2019) and Raj et al. (2019), and their $g - i$ color maps.

We listed the total magnitudes of these galaxies in the g -band, as well as the average $(g - r)$ and $(u - g)$ colors of these galaxies within one effective radius in Table 4.1 from Venhola et al. (2018). In addition we presented the morphological type of the galaxy and whether it is detected in FIR, H I or CO. For the morphology we used Venhola et al. (2018) when it was not consistent with Ferguson (1989), so we can choose the one which is more confirmed by our results; FCC67, FCC261, FCC282. Just for FCC90, we prefer the morphology by Ferguson (1989) to the one from Venhola et al. (2018). For the galaxies that we took from Iodice et al. (2019) and Raj et al. (2019), we listed the magnitudes in the g -band and the total average $(g - r)$ and $(u - g)$ colors from their tables.

In Figure 4.1 the difference between the $g - r$ color of the galaxies presented in 4.1 and their color on the CMR (Roediger et al. 2017), $(g - r) - (g - r)_{CMR}$, is plotted versus their magnitudes in the g -band. These galaxies are divided into five groups: dwarf early-types(dE), Ellipticals(E), Spirals(S), dwarf Irregulars(dIrr) and lenticular (S0), which are shown in different color in this plot. The division applied here between dE and E as well as S and dIrr is in $M_g = -18.5$. Just as explained in previous chapter for FCC90 we showed it as dE. The dashed line shows the CMR. The galaxies which are above this line are redder than CMR and the galaxies which are below are bluer. In this plot, most of the dEs are near the CMR line, although they are mostly above it which can only be explained by the amount of dust that they have which the $g - r$ color is sensitive to. The situation is the same for Spirals, although they have star formation which makes them blue, having dust causes them to appear redder than the CMR.

We made the same plot for the $u - g$ color of the galaxies in Figure 4.2. The CMR is derived from Roediger et al. (2017). The various morphologies are color coded here as well. These two color-magnitude plots are mostly compatible. Note that in $u - g$ almost all spirals are redder than the red sequence, because of large amounts of dust in their inner effective radius.

Figure 4.3 shows the $u - g$ versus $g - r$ color of the sample. The various morphologies are shown with different color codes. The black dashed line is the color-color relation that is derived from the $u - g$ and $g - r$ CMRs of Roediger et al. (2017). This plot shows how much dust and star formation have moved the galaxies in the color-color diagram, e.g., FCC117 has a very blue color in $u - g$.

Figure 4.1 – The difference between the $g-r$ colors of the galaxies presented in the Table 4.1 and their colors on the CMR versus their magnitude in the g -band. The galaxies are color coded by their morphology; the red and yellow circles are dwarf and giant ellipticals, the black and blue squares represent dwarf Irregulars and Spirals, the green stars are lenticular galaxies. The black dashed line shows the CMR.

Figure 4.2 – The difference between the $u-g$ colors of the galaxies presented in the Table 4.1 and their colors on the CMR versus the magnitude in the g -band. The galaxies are color coded by their morphology; the red and yellow circles are dwarf and giant ellipticals, the black and blue squares represent dwarf Irregulars and Spirals, the green stars are lenticular galaxies. The black dashed line shows the CMR.

Figure 4.3 – The $u - g$ versus $g - r$ color diagram. The galaxies are color-coded based on their morphology. The black dashed line is the color-color line derived from the $u - g$ and $g - r$ CMRs of Roediger et al. (2017) in the magnitude range of $-23 < M_g < -13$ which includes the magnitude range of the galaxies in this sample.

4.5 Discussion

To focus more on the early-types, which are the purpose of this study, we selected the galaxies which are classified as early-type by Ferguson (1989). This selection contains ellipticals (E and dE) and lenticulars (S0): FCC44, FCC90, FCC117, FCC167, FCC177, FCC198, FCC206, FCC207, FCC261, FCC282, FCC332, FCC335. We also have added FCC67 which is classified as early-type in Venhola et al. (2018) despite Ferguson (1989), who classified it as spiral.

4.5.1 Early-type galaxies with CO detection

In the Zabel et al. (2019) sample, 15 out of 30 galaxies are detected in CO from which 8 galaxies are early-types: FCC67, FCC90, FCC167, FCC207, FCC261, FCC282, FCC332 and FCC335. In Figures 4.7 to 4.10 we present CO maps (from Zabel et al. 2019) and color maps (both $g - r$ and $u - g$) of all the galaxies with CO detection, both early- and late-types, to have a better overview of the regions with CO, and to be in a better position to compare them with the optical color maps. For galaxies that we took from Iodice et al. (2019) and

FCC	Dust	Young	Alignment	Position	Position
number		Populations		w.r.t. $g - r$ CMR	w.r.t. $u - g$ CMR
(1)	(2)	(3)	(4)	(5)	(6)
90	Y	Y	Y	Bluer	Bluer
207	Y	Y	Y	Redder	Bluer
261	Y	Y	Y	Redder	Bluer
282	Y	Y	Y	Redder	Bluer
332	Y	N	Y	Redder	Redder
335	Y	Y	Y	Redder	Redder

Table 4.2 – Matching the dwarf early-types with CO emission to the the dust patches and young populations in their color maps:

(1) Name of the galaxy from the FCC, (2) presence of dust in the color maps (Y: Yes, N: No), (3) presence of young populations in the color maps (Y: Yes, N: No), (4) alignment of CO with dust and young populations, (5) the position of the galaxy compare to $g - r$ CMR (Redder or Bluer than CMR), (6) the position of the galaxy compare to $u - g$ CMR (Redder or Bluer than CMR).

Raj et al. (2019), we show the only available color map in their paper which is $g - i$. The orientation of the CO and color maps are the same. In the next section we will focus on each individual galaxy with CO detection. In the case of spiral galaxies, it is common knowledge that they contain CO, since they are known to form stars.

Here we will discuss whether CO emission could result in identification of counterparts in the optical images of the dwarf early-type galaxy, e.g., is there any sign such as dust and blue young populations in the color maps, unsharp masks or residual maps of the galaxy. In Table 4.2, we listed only the dEs with CO emission in our sample and checked whether CO maps are consistent with patches of dust and young population that we see in their color maps. Also we presented whether they are bluer or redder than CMRs in Figures 4.2 and 4.1. We summarize this Table as all the dEs with CO show some patches of dust and also almost all of them appear to have young populations of stars in their color maps. Just for FCC332, we did not find any clear young populations regions in its color maps and profiles. In addition other than FCC90, which there is a doubt whether it is a dwarf early-type or a dwarf Irregular, all the dEs appear redder than the CMR in the $g - r$ color which is a clear result of their dust. In the $u - g$ color, they are either bluer or redder than CMR.

To compare this sample with ordinary dEs, we used the sample of Hamraz et al. (2019). In that paper (the previous chapter), we have 26 dEs from the Fornax

Figure 4.4 – *Unsharp masked images of dwarf early-type galaxies in g -band with CO detection in this Chapter. The size of each image is 50×50 arcsecond.*

cluster observed with the HST for which we presented their color maps, unsharp masked images and color profiles in $g - z$ in Figures 3.2 to 3.7. To reduce the resolution of HST images in order to be comparable with the resolution of FDS images, we convolved the images of these 26 galaxies with a Gaussian function. In addition, we also made the pixel size of the images similar to FDS. Then we made unsharp masked images from these convolved images, show them in Figure 4.5 and 4.6 and compare it to the unsharp masked images of the dwarf galaxies with CO in this chapter in Figure 4.4. Studying their color maps and unsharp masked images, there are five galaxies which have some dusty patches and young star populations; FCC26, FCC90, FCC119, FCC152, FCC335. Two of them are in common with the sample of this Chapter; FCC90 and FCC335 which both have CO detection. Other color maps and unsharp masked images do not show any obvious features. These results are presented in Table 4.3. All of these galaxies are bluer than the $g - z$ CMR except FCC119, which is located on the CMR.

4.5.2 Individual dEs with CO detection

Here we discuss each of the early-type galaxies with a CO detection:

FCC90: This galaxy is classified as a late-type by Venhola et al. (2018) whereas Ferguson (1989) claimed it to be an elliptical. Based on its residual image shown in Figure 4.12, this galaxy should be an edge on spiral or

FCC number (1)	Dust (2)	Young Populations (3)	Compare to $g - z$ CMR (4)
19	N	N	Bluer
26	Y	Y	Bluer
55	N	N	-
90	Y	Y	Bluer
95	N	N	Redder
100	N	N	-
106	N	N	Redder
119	Y	Y	-
136	N	N	Redder
143	N	N	Redder
148	N	N	Bluer
152	Y	Y	Bluer
182	N	N	Redder
190	N	N	Redder
202	N	N	Redder
203	N	N	Redder
204	N	N	Redder
249	N	N	Redder
255	N	N	Bluer
277	N	N	Redder
288	N	N	Bluer
301	N	N	Redder
303	N	N	Bluer
310	N	N	Redder
324	N	N	Redder
335	Y	Y	Bluer

Table 4.3 – Table of dust patches and young populations in the color maps of the dEs of our control sample:

(1) Name of the galaxy from the FCC, (2) presence of dust in the color maps (Y: Yes, N: No), (3) presence of young populations in the color maps (Y: Yes, N: No), (4) position of the galaxy compare to $g - z$ CMR (Redder or Bluer than CMR), When the galaxy is on the CMR, it is shown by a '-' sign.

Figure 4.5 – Unsharp masked of the convolved images of dwarf early-type galaxies in *g*-band from Chapter 3 as the control sample. We made the resolution and pixel size of the *HST* images compatible with the *FDS* images. The size of each image here is 80×80 arcsecond. To compare FCC90 and FCC335 in both observation, one should rotate the *HST* unsharp masked images 90 degree counterclockwise in order to be in the same orientation as the *FDS* unsharp masked images.

Figure 4.6 – Figure 4.5 continued.

an elliptical with substructures. We considered this galaxy as dE. Considering the color profiles and color maps it has a noticeable blue center. The CO map is lopsided to the west which is also detectable as a similar color gradient especially in $u - g$ color map in Figure 4.7. This galaxy is bluer than CMR in both $u - g$ and $g - r$ colors. Zabel et al. (2019) compare the direction of the CO tail and the center of the cluster and claims that this galaxy may be experiencing ram pressure stripping as it is falling to the cluster. The effect of the ram pressure is inciting star formation, causing the blue region in the $u - g$ map.

FCC207: This galaxy is a dE with a bluer center from the color profiles. Zabel et al. (2019) described that it has an off-center distribution of the molecular gas which is distinguishable especially in its $u - g$ color map as structure with different color. This galaxy has the same color as the CMR in the $u - g$ color in Figure 4.2 and a bit redder color than the CMR in the $g - r$, Figure 4.1.

FCC261: It has a bit off-centered molecular gas. This off-centered structure is especially visible in the residual map and g -band images and also in the $u - g$ color map. In the $u - g$ color profile of the galaxy, it is seen by the reddest point of the profile around $10''$. It has a bluer color in the $u - g$ than the CMR and almost the same color as the CMR in the $g - r$.

FCC282: This galaxy has some structures which is very clear in the residual and color maps. The molecular gas is located off-center which is comparable to the structures seen in the color maps. The galaxy has a bit bluer (redder) color than the CMR in the $u - g$ ($g - r$).

FCC332: This galaxy has off-centered molecular gas which is distinguishable in the $u - g$ color map by a red dusty center in Figure 4.8. Considering its color profiles, it has a redder center. It is redder than the CMRs in both $u - g$ and $g - r$.

FCC335: Zabel et al. (2019) discussed that the CO emission extends in a tail which points towards the center of the cluster. They claimed that it could be the result of ram pressure stripping which is stripping the gas as the galaxy goes from the center to the outer part of the cluster. In the residual map of this galaxy, there is a dusty patch at the position of the CO contours. It is redder than the CMRs in both $u - g$ and $g - r$.

4.6 Conclusion

In this chapter we studied a complete sample of the galaxies in the Fornax cluster which have been detected in CO. We especially narrowed our focus on dwarf early-type galaxies. We used a sample of 30 galaxies with different morphology from which 15 of them was detected in CO. Six galaxies out of these 15 are dwarf early-types ($M_g > -18.5$); FCC90, FCC207, FCC261, FCC282,

FCC332, FCC335. All of these galaxies show star forming and patchy dust structure in their color maps and residual maps, comparable with CO maps.

In addition, we used the dEs from Hamraz et al. (2019) as our control sample which are selected regardless of the CO emission, Figure 4.5 and 4.6. We found that only $(19\% \pm 3\%)$ of the dEs in that sample of the Fornax cluster show some signs of dust and young stellar populations regions in their color maps and unsharp masked images.

We conclude that all galaxies which have been detected in CO show both blue young populations and dust, mostly in the same place where the CO is found, when studying color maps in the $u - g$ and $g - r$. Comparing these objects to the dwarf early-types without CO detection from previous chapter, we find that the latter have more regular appearance without many distinguishable substructures. Although these visible features in a dwarf early-type galaxy can not directly predict the presence of the molecular gas, it can be used as a probable hint to CO emission.

Appendix

4

4.A Color profiles and color maps

Figure 4.7 – $(g-r)$ and $(u-g)$ color maps of galaxies detected in CO, with Co map on g-band image from Zabel et al. (2019). Galaxies are as follow: FCC67, FCC90, FCC207, FCC261. The center of the galaxy is shown with a black or white star sign in color maps of FCC207 and FCC261 since it is not clear.

Figure 4.8 – $(g-r)$ and $(u-g)$ color maps of galaxies detected in CO, with Co map on g-band image from Zabel et al. (2019). Galaxies are as follow: FCC263, FCC282, FCC332, FCC335. The center of the galaxy is shown with a black or white star sign in color maps of FCC282 since it is not clear.

Figure 4.9 – $(g-i)$ color map of galaxies detected in CO from Iodice et al. (2019) and Raj et al. (2019) sample, with Co map on g -band image from Zabel et al. (2019). Galaxies are as follow: FCC121, FCC167, FCC179, FCC184.

Figure 4.10 – $(g-i)$ color map of galaxies detected in CO from Iodice et al. (2019) and Raj et al. (2019) sample, with Co map on g-band image from Zabel et al. (2019). Galaxies are as follow: FCC290, FCC308, FCC312.

Figure 4.11 – FCC263: first row is color map and color profile in $(g-r)$, second row is color map and color profile in $(u-g)$. The green horizontal line in the color profiles shows color of a galaxy with same magnitude in color-magnitude relation and the green vertical line shows one effective radius. The scale line in color maps shows 50 arc-second. The last row is g -band image and residual respectively in left and right.

Figure 4.12 – FCC90: same as Figure 4.11 caption.

Figure 4.13 – FCC102: same as Figure 4.11 caption.

Figure 4.14 – FCC113: same as Figure 4.11 caption.

Figure 4.15 – FCC115: same as Figure 4.11 caption.

Figure 4.16 – FCC117: same as Figure 4.11 caption.

Figure 4.17 – FCC120: same as Figure 4.11 caption.

Figure 4.18 – FCC198: same as Figure 4.11 caption.

Figure 4.19 – FCC206: same as Figure 4.11 caption.

Figure 4.20 – FCC207: same as Figure 4.11 caption.

Figure 4.21 – FCC235: same as Figure 4.11 caption.

Figure 4.22 – FCC261: same as Figure 4.11 caption.

Figure 4.23 – FCC263: same as Figure 4.11 caption.

Figure 4.24 – FCC282: same as Figure 4.11 caption.

Figure 4.25 – FCC302: same as Figure 4.11 caption.

Figure 4.26 – FCC306: same as Figure 4.11 caption.

Figure 4.27 – FCC332: same as Figure 4.11 caption.

Figure 4.28 – FCC335: same as Figure 4.11 caption.

Figure 4.29 – FCC121 and FCC179: $(g-r)$ and $(u-g)$ color profiles, $(g-i)$ color map and g -band images of the galaxies from Raj et al. (2019).

Figure 4.30 – FCC285 and FCC290 : Figure 4.29 continue.

Figure 4.31 – FCC308 and FCC312: Figure 4.29 continue.

Figure 4.32 – FCC167 and FCC177: $(g-r)$ and $(u-g)$ color profiles, $(g-i)$ color map and r-band images of the galaxies from Iodice et al. (2019).

Figure 4.33 – FCC184: Figure 4.32 continue.

Conclusion

Dwarf galaxies are the most abundant galaxies in the Universe. Since they are faint and small in size, they have not been studied as much as other types of galaxies. In this thesis, we investigated the physics of dwarf early-type galaxies by studying their colors, as a proxy of their stellar populations, and their scaling relations. We also explored how the environment of these galaxies influences their properties. We tried to understand the physics of dwarf early-type galaxies (dEs) more by studying their colors using high resolution photometric images to not only study the outer parts of these galaxies, but also to zoom into the very inner regions as small as a few parsec to investigate their center in nearby clusters as well. We explored color-magnitude diagrams of dwarf early-type galaxies and investigated what information can be extracted from the position of a galaxy on the color-magnitude diagram. In addition, we used the color profile of each galaxy to find out how its color changes from the innermost part of a galaxy to its outer part. Besides color, we measured more photometric properties such as effective radius, magnitude, etc.

We conclude stating the main results of this thesis as below:

Chapter 2: Here, we calculated and tabulated the magnitudes, colors and effective radii of bright dwarfs in the Fornax cluster from the high quality HST observation. We then compared the CMD of early-type dwarfs in the Fornax cluster with similar-size galaxies in Virgo and Coma. Since the observational errors are small, because of the photometric precision of HST, we have been able to study the scatter in the CMR in detail and compare the three clusters. We find that the scatter in the CMR in Virgo is considerably larger than in Fornax and Coma. The scatter is due to the presence of young stars, causing galaxies to lie blueward of the CMR, and by compact early-type galaxies,

which lie redward of it. The main results are:

- We found that in the magnitude interval of $-18.7 \leq M_{g'} \leq -16.0$, the scatter in the CMR is the highest in Virgo, 0.144 mag. In Fornax and Coma the scatter is 0.060 and 0.065 mag, respectively. The large number of outliers on its blue side shows that the Virgo cluster dwarfs are still quite actively forming stars. The same is true for the Fornax cluster.
- The scatter on the blue side of the CMR is due to galaxies with young stellar populations. This is mainly the case in Fornax and Virgo. Their fractions are $11\% \pm 2\%$, $15\% \pm 3\%$, and $2\% \pm 1\%$ of the total dwarf early-type galaxies in Fornax, Virgo, and the central regions of Coma, respectively. The galaxies in Fornax and Virgo in general are probably somewhat younger.
- The situation with the red outliers is totally different in Virgo, as compared to the other clusters. All the red outliers of the color–magnitude diagram in the Virgo cluster are compact ellipticals. Their redder color can probably be explained by tidal interactions with large nearby massive galaxies. There are three red outlier compact galaxies in Virgo and none in the Fornax and Coma clusters. The fact that there are more red outliers in Virgo, a cluster with more ongoing interactions, and that these are cEs, probably means that the environment is still very active, with many galaxy–galaxy interactions, more than in the other clusters. To fully test this idea, much larger sample sizes are needed for statistical significance.

Chapter 3: In this chapter, we used the HST Advanced Camera for Surveys for the Fornax, Virgo and Coma clusters to describe and parameterize the $(g - z)$ color profiles of dwarf early-type galaxies in the magnitude range of $-18.7 \leq M_B \leq -16.0$. The main results of this chapter are:

- The most important result is the large number of blue-cored dEs in all three clusters: all galaxies in the Fornax cluster sample, $85\% \pm 2\%$ of the Virgo sample, and a lower limit of $53\% \pm 3\%$ in the Coma cluster sample, which is discussed in detail in Section 3.4.2. Considering the very distinct characteristics of these clusters and the distribution of these galaxies in each cluster, their formation and evolution are influenced by different factors and cannot be explained by a single theory. The possible scenarios are presented in Section 3.5.1.
- A trend that brighter galaxies generally have negative color gradients, which become less negative and even positive for our faintest galaxies, can be found in the color gradients of all three clusters.
- The bluest cores are found in the faintest galaxies. There is no obvious correlation between the sizes of the blue cores and the luminosity of their host galaxies in any of the clusters.

Chapter 4: In this chapter we studied a complete sample of the galaxies in the Fornax cluster which have been detected in CO. We especially narrowed our focus on dwarf early-type galaxies. We used a sample of 30 galaxies with different morphology from which 15 of them was detected in CO. Six galaxies out of these 15 are dwarf early-types ($M_g > -18.5$); FCC90, FCC207, FCC261, FCC282, FCC332, FCC335. All of these galaxies show star forming and patchy dust structure in their color maps and residual maps, comparable with CO maps.

In addition, we used the dEs from Hamraz et al. (2019) as our control sample which are selected regardless of the CO emission. We found that only ($19\% \pm 3\%$) of the dEs in that sample of the Fornax cluster show some signs of dust and young stellar populations regions in their color maps and unsharp masked images.

We conclude that all galaxies which have been detected in CO show both blue young populations and dust, mostly in the same place where the CO is found, when studying color maps in the $u - g$ and $g - r$. Comparing these objects to the dwarf early-types without CO detection from previous chapter, we find that the latter have more regular appearance without many distinguishable substructures. Although these visible features in a dwarf early-type galaxy can not directly predict the presence of the molecular gas, it can be used as a probable hint to CO emission. We also note that a dwarf early-type galaxy with molecular gas can be both bluer or redder than the CMR.

5.1 Future Prospects

We discussed in this thesis how the different characteristics of a cluster can affect the properties of its galaxies. For instance, an active cluster like Virgo with more ongoing interactions has more outliers in the color-magnitude diagram. We have used high resolution data of HST which enabled us to resolve the details of an objects as small as a dwarf early-type galaxies in nearby clusters. The number of clusters, three clusters, and so the number of galaxies in them that has been studied in this thesis is relatively limited. To confirm our ideas in other clusters, we need large samples of clusters with several galaxies per cluster, observed with high spatial resolution comparable to the HST. This goal can be achieved in several ways:

One way to achieve this goal is to use the archived images of clusters observed with the HST. The Cluster Lensing And Supernova survey with Hubble (CLASH) observed 25 massive galaxy clusters with HST's panchromatic imaging capabilities using Advanced Camera for Survey (ACS) and Wide-Field Camera 3 (WFC3). These observations are all available on the MAST archive now.. The red-shift of the observed cluster is between 0.187 and 0.890, which

means that for the nearest clusters many dwarfs are still well resolved. The data also include some lensed galaxies at higher redshift behind these clusters, also with a high spatial resolution.

Secondly, the Multi-Adaptive Optics Imaging CameraA for Deep Observations (MICADO) will be the first dedicated imaging camera in Near-infrared wavelength for the ESO's Extremely Large Telescope (E-ELT) with first light in 2025. Its sensitivity is comparable to JWST with six times higher resolution, much higher than HST. This is a great tool which will help astronomers to understand what the evolutionary status of a cluster is, but also to study cluster evolution with red-shift.

In addition to these, a big step to explain the current-day form of galaxies is to investigate how their predecessor have formed and then evolved to their current-day shape. The James Webb Space Telescope (JWST) which is a large infrared telescope which will be launched in 2021. One of the main goal of this telescope is to find the answer to many open questions about dwarf galaxies. It will study the formation of galaxies in the first place at higher redshift, and then their evolution in time, leading to the huge variety of galaxies we see today.

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Nederlandse Samenvatting

De kleur van een sterrenstelsel bevat belangrijke informatie over diens evolutie. Het doel van dit proefschrift is om een beter begrip te krijgen van de fysica van vroeg-type dwergstelsels (dwarf early-type galaxies of dE's) door middel van het bestuderen van hun kleuren met behulp van afbeeldingen met een hoog oplossend vermogen. We onderzoeken niet alleen de buitendelen van deze sterrenstelsels, maar zoomen ook in op het binnengebied, tot de binnenste paar parsec (of lichtjaar), om ook de belangrijke middelpunten van nabijgelegen melkwegstelsels te onderzoeken. Eén van de manieren die wij gebruiken bij de analyse van de kleuren is het kleur-magnitude diagram, waarin we onderzoeken welke informatie kan worden verkregen uit de positie van vroeg-type melkwegstelsels. Daarnaast gebruiken we het kleurprofiel van elk sterrenstelsel om te achterhalen hoe de kleur verandert van het binnenste deel van een sterrenstelsel naar de buitendelen. Naast kleur meten we ook andere fotometrische eigenschappen zoals effectieve straal, grootte, enz.

Voor deze studie hebben we een sample van vroeg-type dwergstelsels in het Fornax-cluster gebruikt. Om te onderzoeken hoe de omgeving, waarin dit stelsel zich bevindt, de kleur van zo'n dwergstelsel kan beïnvloeden, vergelijken we ons sample met vergelijkbare samples uit de Virgo- en Coma-clusters. De verschillen in omgevingen tussen deze clusters kunnen ons helpen om de effectieve processen te vinden die verantwoordelijk zijn voor de vorming en evolutie van deze sterrenstelsels. Van de nabijgelegen clusters is Virgo het meest bestudeerd. Na Virgo, met een afstand van 16.5 Mpc, is Fornax, met een afstand van 20 Mpc, de dichtstbijzijnde grote concentratie van sterrenstelsels in het Zuiden (Blakeslee et al. 2009). Vergeleken met Virgo is het Fornax-cluster minder massief, kleiner en heeft het een ondieper potentiaal, terwijl Virgo een

rijkere en activere cluster is met allerlei soorten interacties tussen sterrenstelsels onderling en tussen sterrenstelsels en hun omgeving, zoals ram-pressure stripping, tidal stirring en galaxy harassment. Coma is een zeer rijke cluster op een afstand van 100 Mpc (Carter et al. 2008) met een hoge dichtheid van melkwegstelsels. Deze locale dichtheid van stelsels in de omgeving van een melkwegstelsel speelt een belangrijke rol bij het bepalen van de evolutie van een stelsels, wanneer sterren worden gevormd en uitdoven, en daarmee bij het bepalen van de kleur.

De belangrijkste waarnemingen die in deze studie worden gebruikt komen van de waarnemingen van de Hubble Space Telescope/Advanced Camera for Surveys (HST/ACS). De HST waarnemingen komen van de ACS Fornax Cluster Survey (ACSFCS), de ACS Virgo Cluster Survey (ACSVCS) en de HST/ACS Coma Cluster Survey. De ACSVCS- en ACSFCS-waarnemingen zijn gemaakt voor samples van de helderste 100 resp. 43 sterrenstelsels in Virgo en Fornax. De afbeeldingen zijn beschikbaar in het HST Mikulski-archief. Voor het Coma-cluster werd slechts een beperkt deel van het cluster waargenomen, meestal in de centrale regio's, omdat hen hier een heel gebied aan de hemel in kaart wilde brengen, en niet slechts de helderste stelsels, maar ook omdat de ACS-camera in de latere fase van het onderzoek faalde. We hebben onze samples van melkwegstelsels beperkt tot stelsels in een specifiek magnitudebereik, die meestal de heldere vroeg-type dwergsterrenstelsels worden genoemd.

Ondanks het feit dat dit vroeg-type melkwegstelsels zijn, die dus voor het grootste deel bestaan uit rode, oude sterren, bevatten ze vaak ook blauwe gebieden, die de vorming van jonge sterren aangeven, en verroding door stof. Om te begrijpen of deze blauwe stervormingsgebieden en de gebieden met stof in de kleurenkaarten van een dE de aanwezigheid kunnen voorspellen van moleculair gas, hebben we bovendien een sample geselecteerd van stelsels in de Fornax cluster waarin koolmonoxide (CO) is gedetecteerd, en hebben de kleuren hiervan bestudeerd. CO is het meest waargenomen tracer-molecuul waterstof (H_2) (Narayanan & Krumholz 2014). Daar H_2 fundamenteel is voor de vorming van sterren, gebruiken we de detectie van CO als een tracer die de vorming van sterren aangeeft. Voor deze stelsels hebben we de afbeeldingen gebruikt van deze sterrenstelsels in de Fornax Deep Survey (FDS) om hun kleurenkaarten en kleurprofielen te onderzoeken. De FDS is een nieuwe survey van het Fornax-cluster, gemaakt met behulp van de ESO VLT Survey Telescope (VST), en bevat 573 sterrenstelsels in de banden u, g, r en i, die met behulp van het OmegaCAM-instrument op de VST in Chili zijn waargenomen. De belangrijkste resultaten van dit proefschrift zijn als volgt:

Hoofdstuk 2: Hier hebben we het gedrag bestudeerd van vroeg-type dwergstelsels in de kleur-magnitude-relatie (CMR) en diens relatie tot de omgeving van deze stelsels. We presenteren kleur-magnitude-relaties voor drie nabijgelegen clusters: Fornax, Virgo en Coma. We gebruikten afbeeldingen van de Hubble

Space Telescope (HST) van sterrenstelsels in de Fornax-cluster in het magnitudebereik van $-18.7 \leq M_B \leq 16.0$, en vergelijken stelsels in deze cluster met die in Virgo en Coma. De fotometrische stabiliteit van HST maakt het voor ons mogelijk om zeer nauwkeurige kleurmetingen te verkrijgen, en om de reden achter de scatter in de CMR te begrijpen. Als we de CMR's van de drie clusters vergelijken, kunnen we zien dat de scatter in Virgo aanzienlijk groter is dan in Fornax en het centrum van Coma. De sterrenstelsels aan de blauwe kant van de CMR vertonen blauw licht van jonge sterren, verzwakt door stofuitdoving, in de kernen van de sterrenstelsels of de meer uitgebreide structuren. De meeste uitschieters aan de rode kant zijn compacte vroeg-type sterrenstelsels, met oppervlaktehelderheidsprofielen die 'afgekapt' zijn in de buitendelen, en vaak metgezellen van de grote sterrenstelsels zijn. Interessant is dat er in dit magnitudebereik geen rode, compacte uitschieters zijn gevonden in Fornax en Coma, terwijl we er drie vinden in het Virgo-cluster. We hebben ook vastgesteld dat de CMRs van de Fornax- en Virgo-clusters iets blauwer zijn dan die van Coma. We betogen dat de kleine scatter van de CMR kan worden gebruikt als een effectief hulpmiddel om de vorming van sterrenstelsels en hun sterpopulaties te bestuderen.

Hoofdstuk 3: In dit hoofdstuk hebben we data van de Hubble Space Telescope Advanced Camera for Surveys voor de Fornax-, Virgo- en Coma-clusters gebruikt om de (g-z) kleurprofielen van vroeg-type dwergsterrenstelsels in het groottebereik van $-18.7 \leq M_B \leq 16.0$ te beschrijven en te parametriseren. Het belangrijke resultaat van dit hoofdstuk is dat we in alle drie de clusters een groot aantal vroeg-type dwergstelsels met een jonge sterpopulatie in hun centrum hebben aangetroffen: in Fornax is dit het geval in het hele sample, in Virgo bij $85\% \pm 2\%$ en in het Coma-cluster bij $53\% \pm 3\%$ van de stelsels. We toonden aan dat blauwere kernen zich in zwakkere dE's bevinden. Deze blauwe kernen zijn vergelijkbaar met zogeheten nuclear clusters, die zich in verschillende dE's bevinden, maar zijn over het algemeen groter. We hebben geen verband gevonden tussen de helderheid van een sterrenstelsel en de grootte van zijn blauwe kern. Gezien de zeer verschillende kenmerken van deze clusters, en de verdeling van deze sterrenstelsels in elk cluster, is het moeilijk worden hun vorming en ontwikkeling toe te schrijven aan een enkel fysisch effect, maar het is duidelijk dat omgeving een grote rol speelt.

Hoofdstuk 4: In dit hoofdstuk hebben we de optische eigenschappen van het sample van Zabel et al. (2019) bestudeerd, een compleet sample van sterrenstelsels waargenomen met de submm telescoop ALMA in de Fornax-cluster, met of zonder detecties. We hebben voor dit sample de afbeeldingen van de Fornax Deep Survey (FDS) gebruikt om de kleurprofielen en kleurenkaarten van deze sterrenstelsels in de optische banden te onderzoeken. Vervolgens hebben we ons gericht op de vroeg-type dwergsterrenstelsels uit deze steekproef en deze vergeleken met die zonder moleculair gas, om te onderzoeken of de

aanwezigheid van moleculair gas verband houdt met kenmerken die optisch te onderscheiden zijn. We hebben hier de kleurprofielen en kleurenkaarten in $g - r$ en $u - g$ gebruikt, evenals de residuen van de kaarten van deze stelsels, waar een model met concentrische ellipsen is afgetrokken van de originele waarnemingen. We vinden dat CO-gedetecteerde sterrenstelsels veel onderscheidbare substructuren hebben in hun kleurenkaarten en profielen, meestal op dezelfde plaats waar de CO wordt gevonden. De andere vroeg-type dwergsterrenstelsels zonder CO-uitstoot blijken daarentegen regelmatig. Hoewel dergelijke zichtbare kleursubstructuren zoals blauwe jonge populaties en stof in een vroeg-type dwergsterrenstelsels niet direct de aanwezigheid van moleculair gas kunnen voorspellen, kan het worden gebruikt als een waarschijnlijke indicator.

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