Kinematics and stellar populations of dwarf elliptical galaxies
Mentz, Jacobus Johannes

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Document Version
Publisher's PDF, also known as Version of record

Publication date: 2018

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

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Chapter 1

Introduction

1.1 Galaxies and galaxy classification

Less than a century ago, the foundation of extragalactic astronomy was laid with the realization that individual stellar systems exist outside our own Milky Way galaxy. This came as a result of careful observations by Edwin Hubble (Hubble 1929), who determined that the Andromeda galaxy (M31) is more distant than observable objects belonging to the Milky Way. This was a remarkable discovery in the field of observational astronomy, which led to the observational pursuit of more types of objects with ever increasing questions about their existence. Today we know that the Milky Way is one of many billions of galaxies in the observable universe. Even though it is a vast stellar system by itself, we are able to study it in increasing detail in order to learn more about its properties and dynamical characteristics by analysing stellar motions and structures within the galaxy. In a similar fashion, although hampered by their large distances from which we are mostly unable to resolve individual stars, we are able to study other distant galaxies beyond the boundaries of the Milky Way using various spectroscopic and photometric techniques.

Galaxies are known to be mostly gathered in gravitationally bound structures, called groups and clusters (Binggeli, Sandage & Tammann, 1988; Moore
1.1. Galaxies and galaxy classification

Figure 1.2 – Updated version of the original classification scheme by Kormendy & Bender (1996), which accommodate on the fork branches the class of irregular galaxies. The classification for early-type galaxies was also updated to distinguish between disky and boxy shapes.

Bergh (1960) Addition of luminosity classes; Elmegreen & Elmegreen (1982) Spiral arm classification; Sandage & Bedke (1994) Expanding spiral/dwarf galaxy classification scheme. These revisions were required due to the very diverse morphological nature of observed galaxies, which include other types and subclasses of galaxies, eg. irregular galaxies and dwarf elliptical galaxies (dEs), the latter type is of main interest in this study. Improved observational capabilities in the detection of lower surface-brightness objects also contributed to the expansion of different sub-classes. It is important to note that Hubble’s original classification was mostly based on bright giant spiral galaxies and needs to be adapted to accommodate properties as observed in dwarf galaxies. According to an early red shift-apparent magnitude relation by Humason, Mayall & Sandage (1956), dwarf galaxies initially appeared to belong to the Sc type (van den Bergh, 1960). Lin & Faber (1983) were the first to indicate a possible evolutionary link between dwarf irregular galaxies and dEs, based on their light profiles and dark matter content. Soon thereafter, Kormendy (1985) concluded that dEs, referred to by them as dwarf spheroidals, are more closely related to dwarf spirals and irregular galaxies because of their nearly identical light profile within the core region. From this they proposed that dEs possibly originate from dwarf spirals or irregulars which lost their gas content or underwent star forming episodes in their distant past. Kormendy & Bender (1996) proposed another revision of the Hubble classification scheme (Figure. 1.2) in which they introduce disky and boxy ellipticals and added the irregular class, whose properties closely resemble those of dEs.
1.2 Dwarf elliptical galaxies

The main reason why the dE class attracts much attention is the fact they are the most numerous galaxies in the universe. Even though they dominate most galaxy clusters in their absolute numbers, their properties are still largely unknown due to the difficulty to observe them in detail. Some of the main questions that arise when studying this type of galaxies relate to their formation and evolution and why they are only found in cluster environments. To try to unravel these mysteries, it is necessary to study these galaxies by focusing on their structural properties, stellar populations, and the environmental impact on these systems. As an additional tool, scaling relations can be used in order to compare or link properties to other galaxy classes.

As a widely-accepted definition, dEs are defined as low luminosity and low surface-brightness galaxies with an exponentially declining radial surface brightness profile. They cover an absolute B-magnitude range between -15 and -18 mag and have also been found to have lower metallicities compared to their massive elliptical counterparts.

By studying the optical luminosity function (LF) of dEs, which is a probability distribution function for galaxies of any specific Hubble type, Binggeli, Sandage & Tammann (1988) showed that the LF of dEs only dominates in cluster environments (Figure 1.3). This raised the important question on why isolated dEs are not found outside galaxy clusters. This was also found to be in agreement with the morphology density relation (Dressler 1980; Binggeli, Tammann & Sandage 1987), indicating early-type galaxies (ETGs) to have much higher numbers in dense cluster environments with very little to none found in the field. Furthermore, it was also noticed that dEs are almost always found to be the closest satellite galaxies of massive elliptical galaxies, with galaxies further afield belonging to the spiral or irregular types (Einasto et al., 1974).

1.2.1 Structural properties

Morphology

Many studies have tried to address the question whether dEs constitute a low surface-brightness extension of giant ellipticals or whether they belong to a subclass of their own. Kormendy et al. (2009) verified that a strong dichotomy exists between the giant elliptical and dEs classes (Figure 1.4). They argue that the properties of these two classes of elliptical galaxies appear to correspond to two different formation processes. A history of mergers seems to describe the formation of massive ellipticals, while the transformation from late-type galaxies by environmental effects seems more appropriate in the case of dEs. However, the question on different formation mechanisms remains open to interpretation, as illustrated by the attempts to explain the properties of dEs in continuity with
Figure 1.3 – Luminosity function of galaxies, showing a comparison of the contribution of different galaxy types to the total luminosity as observed in the field (top) and in the Virgo cluster (bottom). From Binggeli, Sandage & Tammann (1988).
those observed for giant elliptical galaxies as shown in Figure 1.5 (Graham & Guzmán, 2003; Graham, 2013).

Another strong argument for the case of dEs being transformed late-type galaxies was raised by Einasto et al. (1974) who showed that their morphology appears to be dependant on the distance from large companion galaxies. In this scenario, the galaxies get stripped of their gas content by a rich gaseous halo found around the companion galaxy. This morphological transformation has a direct effect on the quenching of star-formation, which leads to a smooth morphological appearance (Lisker et al., 2006). Apart from the overall smooth appearance, it has also been found that some of the brighter dEs contain a strong nuclear component, consisting of massive star clusters (Binggeli, Sandage & Tarenghi 1984). Nucleation in dwarfs has a higher occurrence in brighter, round-shaped galaxies (van den Bergh, 1986). The formation of these nuclear star clusters (NSCs), which had been found to contribute up to 20% of the total light output (Vader & Chaboyer 1994), is still poorly understood. A few formation mechanisms have been proposed, which include central star-formation as a result of gas moving to the centre of slow rotating dwarfs (van den Bergh 1986) and migration of globular clusters towards the central regions due to dynamical friction induced orbital decay (Oh & Lin, 2000). Côté et al. (2006) argue that the nuclei found in dwarf galaxies closely resemble those found in late-type spiral galaxies in terms of their luminosity and size. A possibility exists that recently discovered ultra compact dwarfs (Hilker et al. 1999; Phillipps et al. 2001) could be the remnant nuclei of dwarf galaxies dissolved by tidal forces as they entered a dense cluster environment.

**Photometry**

Another way to obtain information about the intrinsic structure of these dwarf galaxies is to study the surface-brightness profile and two dimensional isophotes by means of a photometric analysis. Since the early 1980s, photometric measurements have been obtained for a number of dwarfs by analysing photographic plates and later with the use of CCDs (Ferguson & Binggeli, 1994). The use of surface-brightness profiles present a fundamental way in probing the structure of a galaxy. This technique of galaxy decomposition and fitting of the light profile has lead to important advances in understanding galaxy formation and evolution, which include scaling relations and morphological transformations of galaxies in cluster environments (Peng et al., 2002). It has been noted that their surface-brightness profiles are different compared to those of massive elliptical galaxies. The surface-brightness of dwarf early-type galaxies do not conform to Hubble’s $1/r^2$ (Hubble 1930) nor to the de Vaucouleurs’ law (de Vaucouleurs 1948). It was later found that an exponential profile provides a reasonably good description of the dE luminosity profile, in which case it was also postulated that the exponential profile might indicate a closer evolutionary link with the spiral-irregular type (Faber & Lin, 1983). Wirth & Gallagher
Figure 1.4 – Correlations of different galaxy parameters inside isophotes that contain 10% of the total light. These parameters, which include radius ($r_{10\%}$), surface-brightness ($\mu_{10\%}$), and total V-band magnitude ($M_V$) are shown for massive ellipticals and dwarf ellipticals (called “spheroidals” by Kormendy et al. 2009). From Kormendy et al. (2009).
Figure 1.5 – Different interpretations in the relations between the observed surface-brightness and the absolute magnitude of early-type galaxies. Left: Graham & Guzmán (2003) proposed a continuous relation when using the mean- and effective surface-brightness instead of central surface-brightness measurements. Right: Dichotomy between Es and dEs, shown by Kormendy et al. (2009) to be distinct sequences based on inherently different surface-brightness profiles. Adapted from Graham (2013) and Kormendy et al. (2009).

(1984) proposed that brighter compact elliptical galaxies, like M32, could be related to massive ellipticals as a lower luminosity extension, while dEs do not conform to this, as previously thought to be the case. They show that in the case of brighter and more compact dEs, like M32, the surface-brightness profiles could also be described using de Vaucouleurs' law. This revealed another possible distinction in the class of dwarf early-type galaxies, where the more compact ellipticals could be seen as a lower luminosity extension to the luminous giant elliptical class.

Although ellipticals normally appear to be mostly featureless systems, more recent deep photometrical analyses showed these galaxies to have complex underlying structures, which include disks, spiral arms, and irregular features (Jerjen, Kalnajs & Binggeli, 2000; Barazza, Binggeli & Jerjen, 2002; Geha, Guhathakurta & van der Marel, 2003; Graham & Guzmán, 2003; De Rijcke et al., 2003a; Lisker, Grebel & Binggeli, 2006). Peng et al. (2002) showed, by means of photometric decomposition, that giant elliptical galaxies are characterized by the presence of underlying bars, disks, nuclear and gas structures. For dwarf galaxies, Lisker, Grebel & Binggeli (2006) and Lisker et al. (2006, 2007a) conducted a morphological study, in which they applied unsharp masking and performed surface photometry to search for any underlying morphological features. From a sample of 413 Virgo cluster dEs, they found that up to 88% could be classified as normal, of which 51% are nucleated and the remainder weakly to none nucleated. Up to 13% of their sample were found to contain disk features and 5% blue central regions. From these sub-classes it was also noticed that nucleated dEs tends to be more relaxed compared to the more unrelaxed non-nucleated dEs, which could be an indication of a formation scenario involving in-falling progenitor galaxies. It was also found
that non-nucleated dEs in the Fornax and Coma clusters are younger with higher metallicities compared to nucleated dEs (Rakos & Schombert, 2004).

Similarly to the discussion about a discontinuity in the morphological properties between giant and dwarf elliptical galaxies, the photometric relations (e.g., the colour-magnitude relation), also appear to show a dichotomy between the two classes (de Vaucouleurs, 1961; Caldwell, 1983). A strong relation exists for ETGs between the optical colours and luminosities, where more luminous galaxies have redder colours (Baum, 1959; de Vaucouleurs, 1961; Caldwell, 1983; Lisker, Grebel & Binggeli, 2008). The colour-magnitude relation for nucleated early-type dwarfs was found to differ significantly compared to that of non-nucleated dwarfs (Lisker, Grebel & Binggeli, 2008). This revealed that the formation scenarios could in fact be different for nucleated and non-nucleated sub-classes of dwarf early-type galaxies.

**Kinematics and rotational support**

By focusing only on photometry, galaxies might appear relatively uniform, even though they may contain distinct kinematical features. As a first step in the process of extracting kinematic information from galaxies, it is necessary to obtain good quality and high signal-to-noise (S/N) spectroscopic data. For ETGs, especially dwarfs, this requirement already sets a hindrance due to the difficulty to obtain quality spectra for low surface-brightness objects. The exponential decline in luminosity of ETGs also makes good radial coverage more difficult. The first kinematic information for an ETG was extracted by Bertola & Capaccioli (1975) using long-slit spectroscopy. Long-slit spectroscopy relies on the principle of a slit being placed on a galaxy (normally along the major axis), allowing its light to be dispersed for spectral analysis.

In the early 1980s, Courtes (1982) introduced spectroscopy with the use of integral field units (IFUs), which would make use of the ability to extract a spectrum from a single pixel element, thereby creating the possibility that the spatial information of the imaged object can be reconstructed, an idea that revolutionized spectroscopy. Since then multiple IFU instruments were built which created the ability to extract detailed two-dimensional kinematics of galaxies. Despite this technological development in the field of spectroscopy, it is still a very time-consuming task to obtain high S/N spectra of dwarf early-type galaxies due to their low surface-brightness nature.

The kinematics of a galaxy is driven by stellar motion, which can either be dominated by pure disk-like rotation (rotationally supported) or by random orbital motions (pressure supported), where the velocity dispersion of a system is determined from the velocity broadening in the spectral lines. The ratio between the maximum rotational velocity and velocity dispersion, \( V/\sigma \), is classically used as angular momentum indicator. Elliptical galaxies tend to have lower \( V/\sigma \) values compared to spiral galaxies. dEs have been found to show a wide range in rotation, from non-rotating to fast-rotating systems (Geha, Guhathakurta & van
der Marel, 2003; Toloba et al., 2009, 2011; Ryš, Falcón-Barroso & van de Ven, 2013). The reason for such a wide range is still unclear and has to be linked to the different mechanisms involved in their formation and/or environmental factors. As opposed to rotationally supported systems, dEs are found to be pressure supported. In order to quantify rotational support in galaxies, Emsellem et al. (2007) proposed a new kinematic parameter $\lambda_R$, which quantifies the rotational support with integration of the two-dimensional spatial information as provided by IFU instruments. Toloba et al. (2015b) indicated an increase in the fraction of rotationally supported dEs with cluster-centric distance in the Virgo cluster, where pressure supported dEs, on the other hand, are mostly found in the central parts of the cluster. These phenomena can be ascribed to dwarfs that lost their angular momentum due to processes related to the interactions that take place in a dense environment.

By studying the kinematic profiles of dEs, kinematic anomalies in the form of kinematically decoupled cores (KDCs) have also been found (De Rijcke et al., 2004; Toloba et al., 2014b). In the case of more massive ETGs, this is a typical kinematic structure that arises in a merger between galaxies, resulting in a counter rotating or differentially rotating region surrounding the nucleus (Tsatsi et al. 2015). However, for dwarf galaxies, it is unlikely that KDCs could be formed in cluster environments due to the destructive high velocity encounters. De Rijcke et al. (2004) proposed a scenario where dE progenitor galaxies could form KDC structures after lower velocity encounters in smaller groups before they enter a cluster environment.

### 1.2.2 Stellar populations

Stellar population analysis probes the fossil record of galaxy formation. It provides us with clues to the population build-up that occurred in a galaxy during its formation and evolution. Unlike most galaxies in the Local Group, the stellar populations of more distant galaxies cannot be resolved into individual stars. In this case, the spectral analysis has to be done using integrated spectra, with a contribution from all stars in a population (Salaris & Cassisi, 2005). Population synthesis relies on the construction of a set of simple stellar populations (SSPs), which is represented by a particular mass distribution of stars of the same age, metallicity, and chemical abundance pattern. The ingredients necessary to construct an SSP (Eq. 1.1) include isochrones from stellar evolution theory, a library of theoretical or empirical stellar spectra, and an initial mass function (IMF), which dictates the mass distribution of stars used in the SSP (Conroy et al., 2013). With a set of input SSPs, a representable population of the observed galaxy is created by the best fitting SSP or a combination of multiple SSPs. This technique will be at the base of all stellar population analysis done in the thesis. An SSP is constructed by using
1.2. Dwarf elliptical galaxies

the following equation,

$$f_{\text{SSP}}(t, Z) = \int_{m_l}^{m_u(t)} f_{\text{star}}(T_{\text{eff}}(M), \log g(M)|t, Z) \Phi(M) dM$$

(1.1)

where $M$ is the initial stellar mass which is integrated over a lower $m_l$ and upper $m_u$ mass, $\Phi(M)$ is the IMF, $f_{\text{star}}$ represents the stellar spectrum leading to the resulting age and metallicity SSP spectrum $f_{\text{SSP}}(t, Z)$ (Salaris & Cassisi, 2005).

Star formation histories entail the recovery of stellar ages from a composite stellar population system. In contrast to earlier beliefs that all elliptical galaxies are “red and dead” consisting of only old populations (Baade 1944; Morgan 1959), some dEs have shown to contain a diverse stellar composition (Geha, Guhathakurta & van der Marel, 2003; Toloba et al., 2014b). The fact that observational evidence points to more complicated stellar populations which may include young components (Ryš et al. 2015) suggests that recent star formation activity took place in some cluster-bound, interacting dEs (Moore et al., 1996). A young stellar population also suggests that gas should be present from which the young stars could have formed. This was observed for dEs in the Fornax cluster, which seem to contain a reasonable amount of gas (De Rijcke et al. 2003b; Michielsen et al. 2004). Similarly, in the Virgo cluster, Toloba et al. (2015b) found four dEs with some emission in the Balmer absorption lines. Toloba et al. (2015b) propose a scenario in which the Virgo dEs could be the remnants of late-type star forming galaxies which underwent incomplete gas removal by ram pressure stripping. De Rijcke, Buyle & Koleva (2013) also observed a dE (FCC 46) in the Fornax cluster with evidence of a gaseous counter-rotating polar ring, supplying gas to sustain ongoing star-formation in the central region.

1.2.3 Environment

By studying the different structural components of these dwarf systems, some of the fundamental questions on the environmental influence on galaxy evolution can be addressed. The environmental effects on these low surface-brightness systems are amplified by their shallow gravitational potential, which makes for even greater susceptibility towards internal and external mechanisms compared to their larger counterparts (Lisker et al., 2013; Ryš, Falcón-Barroso & van de Ven, 2013).

A detailed study of the formation and evolution of this class of galaxies therefore involves a link between their characteristics, which include the kinematics, angular momentum, and stellar populations to the environmental influence on the system. The discovery of substructures in dEs could suggest that one of the main hypotheses that these systems could be seen as remnants of late-type spiral or irregular galaxies, which were transformed through recurrent interactions with massive galaxies in clusters (Moore et al., 1996; Lisker et al.,
2006; Lisker, Grebel & Binggeli, 2006; Koleva et al., 2009a). It is believed that the interaction with the hot intra-cluster medium causes the gas in dwarf galaxies to disappear (Gunn & Gott 1972; Boselli & Gavazzi 2006), so that the galaxy slowly becomes a dE. However, quantitatively this picture is not very clear yet, and currently very little is known about the formation mechanisms involved in the transformation of dEs, where multiple scenarios have been proposed. They include processes which should be able to remove gas from the system and thus being responsible for quenching star formation. Another important property that these mechanisms should be able to explain is the fact that some dEs are observed to be slow rotators or pressure supported systems, which are mostly found in the central parts of clusters (Toloba et al., 2015b). The quest is then to find mechanisms that could explain both the removal of the gas content and apparent loss of angular momentum in dEs. Ram-pressure stripping involves the interaction of a galaxy with the intergalactic medium (Gunn & Gott, 1972). The galaxy experiences an external pressure force as it moves through the cluster where the force depends on the density of the intergalactic medium as well as on the relative velocity of the galaxy (Schindler & Diaferio, 2008). In the case of ram-pressure acting on an in-falling galaxy, it is expected that its angular momentum should be conserved (Ryš, Falcón-Barroso & van de Ven, 2013). Galaxy harassment has to do with galaxy-galaxy interactions during high speed encounters in the cluster environment together with the effect of the cluster potential well. This can be associated with stellar mass loss and lowering of the intrinsic angular momentum of the system (Moore et al., 1996; Ryš, Falcón-Barroso & van de Ven, 2013). However, the individual effects of either of these two mechanisms or the combined effect is not entirely clear. Bialas et al. (2015) found that galaxies entering a cluster environment do not show significant mass loss from the tidal interaction, where substantial mass loss could however be predicted for galaxies in the central regions of the cluster. They also indicate that other properties, like disk inclination and galactic orbit, could play an important role in the transformation process. They concluded that the morphological transformation process would have to be started at early times in proto-clusters and continue to the current epoch in order to result in the current observed dEs.

1.3 This thesis

In this Ph.D thesis, we investigate the physical properties of dEs by focusing on their kinematics and stellar populations as analysed using integral field spectroscopy. The aim of this study is to help form a better and more complete understanding of the formation and evolution of dEs in the cluster environment.

With this aim in mind, the Virgo galaxy cluster is among the most favourable galaxy clusters for this type of study due to the fact that it is the closest large galaxy cluster. However, it is also a very rich cluster, meaning that multiple
This thesis addresses processes (ram-pressure stripping, tidal stirring, and galaxy harassment) that can operate on galaxies. The thesis combines with the fact that the Virgo cluster consists of several subgroups, making disentangling these processes extremely hard. A natural solution is to observe a less rich cluster and compare the results with those obtained for Virgo cluster galaxies. The Fornax cluster was specifically chosen for this study not only because it is less rich but also because it is more compact in comparison to the Virgo cluster. This allows for a possible amplification of the environmental effects on dwarf galaxies entering the cluster environment.

Our sample consists of 11 dEs evenly distributed in the Fornax cluster. The low surface-brightness nature of these objects justifies the necessity to obtain as deep exposures as possible in order to reach a high S/N ratio in the spectroscopic data. However, deep spectroscopic observations come at a price due to the fact that they are very time consuming and occasionally involve over-subscribed scientific instruments.

As a first study, we obtained IFU data for NGC 1396 using the Multi Unit Spectroscopic Explorer (MUSE) instrument on the Very Large Telescope (VLT) UT4 telescope at the European Southern Observatory (ESO) site in Chile. These observations served as a pilot study to explore the possibilities in observing dEs with this new and state-of-the-art IFU instrument. NGC 1396 is a typical dE located in the centre of the cluster at a close projected proximity to the central massive elliptical galaxy NGC 1399. The aim of exploring this galaxy was to obtain a complete picture of an early-type dwarf galaxy by studying the kinematics and stellar populations of all its components, which include the nucleus, stellar body and globular cluster system. Lisker et al. (2013) indicated that cluster dEs have been exposed to a group or cluster environment for most of their existence. Therefore in analysing all components of this galaxy simultaneously, which carry a fossil record from the different formation epochs, it is possible to trace the history of the environmental influence. In Chapter 2, we present a detailed description of the stellar populations of NGC 1396, focusing on the elemental abundances and the slope of the IMF. The MUSE instrument provides a relatively high spectral resolution with a large wavelength coverage, which enabled us to publish, for the first time, integral field spectroscopy of a dE in the near infra-red region. This region contains important spectral features, including the calcium triplet lines, which are valuable in constraining the IMF and elemental abundances. The MUSE IFU has a very large field of view (FOV) and in combination with a mosaic observing pattern, it gave us an additional advantage of a spatial coverage up to 1.4 effective radii, which also includes the globular cluster system of the galaxy.

The remaining ten galaxies in the sample was observed with the VIsible MultiObject Spectrograph (VIMOS) mounted on the VLT UT3 telescope at ESO. These galaxies were chosen from a magnitude limited sample of 20 galaxies from the ACS Fornax Cluster Survey (ACSFCS) by Jordán et al. (2007), and
represents the brightest galaxies in the sample with magnitudes of $M_B > -18$. The VIMOS instrument has a lower spectral resolution compared to the MUSE instrument and also a much shorter wavelength range. With the larger sample observed by VIMOS, the aim was to gather better information on environmental factors which could depend on cluster-centric distance (Ryš, Falcón-Barroso & van de Ven 2013; Toloba et al. 2015b) and affect galaxies in the sample differently. In Chapter 3, we present our results on the kinematics of these ten galaxies and show velocity and velocity dispersion maps of the sample together with an analysis of the rotational support as function of cluster-centric distance. Our stellar population analysis of the ten galaxies is presented in Chapter 4, where we present star-formation histories of all galaxies with the use of the line-strength index- and full spectral fitting techniques. In Chapter 5, we provide a general overview of our results, conclusions, and comments on future prospects in the field. In Appendix A, we present preliminary results from an analysis of NGC 1396, in which we applied Jeans dynamical modelling.