Brightest Cluster Galaxies As Probes of Galaxy Formation

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Abstract

This thesis addresses open questions related to the formation and evolution of brightest group and cluster galaxies (BCGs). To explore the evolution of BCGs in detail, I have combined different observational techniques. This techniques include analysing the large data set of the Galaxy And Mass Assembly (GAMA) survey, as well as integral field spectroscopy (IFS) from VIMOS on the Very Large Telescope, and SPIRAL on the Anglo Australian Telescope. Thanks to these comprehensive observations I have been able to analyse important tracers of the evolution of BCG. These tracers include their stellar mass growth over time, their star formation and active galactic nuclei activity, their position in their host dark matter halo, and their stellar populations and kinematics. My results are contributing to improving our understanding of these galaxies’ special characteristics and their role in the galaxy evolution process.

From a robust statistical analysis of BCGs from the GAMA survey, I find that at low redshifts ($0 < z < 0.3$) BCGs do not grow significantly in stellar mass. To date, the observed mass growth of BCGs suggests that these galaxies accrete their mass at a fast rate until $z \sim 0.5$; but at lower redshifts their mass growth slows down. I also find that these massive galaxies are not completely dormant. A large fraction ($\sim 0.54$) of BCGs show H$\alpha$ in emission. From this fraction, half are star-forming and half are active galactic nuclei. The fraction of star-forming galaxies decreases with stellar mass, while the fraction of active galactic nuclei remains constant with stellar mass. From the galaxies with ongoing star formation I quantify the star formation rate. The number of stars formed per year decreases with stellar mass, and on average spans from $0$ to $8 \, M_\odot$ per year. I conclude, that despite the fraction of star formation detected in BCGs, the star formation rates are below that needed to contribute to significant growth in their stellar mass.

I further analyse the BCG position with respect to its host cluster and find that 13 percent of the BCGs in the GAMA sample are off-set from their cluster centre. These off-set BCGs reside in halos with low dominance, in high over-density regions, suggesting that these halos have gone through recent mergers. BCGs are massive galaxies. Since star formation does not contribute significantly to their stellar mass growth at low redshifts, galaxy interactions are likely to be the main driver of their mass growth. To investigate the accretion history of BCGs, I present the first IFS stellar population analysis of 9 BCGs. I also investigate whether their accretion histories are different from those of other early-type galaxies. The BCGs have high central
metallicities ([Fe/H] \sim 0.13 \text{ dex}), shallow metallicity gradients (\Delta [Fe/H] \sim -0.11) and a wide range of central ages. The ages can be divided in a bimodal distribution of intermediate central ages (\sim 6.5 \text{ Gyrs}) and old central ages (\sim 12 \text{ Gyrs}). This suggests that these BCGs have diverse accretion histories. I find that three BCGs have similar stellar populations to early-type galaxies of similar mass in the ATLAS3D sample, however, the other six BCGs show a more active accretion history than the early-type galaxies.

Finally, this thesis presents the first analysis of the influence of galaxy stellar mass and cluster halo mass and dominance on the angular momentum of 29 central BCGs at 0 < z < 0.2, including new observations of 12 brightest group galaxies. The stellar mass – halo mass relationship seems to influence the angular momentum of central galaxies. The galaxies evolve from fast-rotating group galaxies to slow-rotating cluster galaxies. Above log M_*(M_\odot) = 11.3 and log M_{200}(M_\odot) = 15 all BCGs are slow rotators. I also find that this trend correlates with the dominance of its host cluster, suggesting that the BCG angular momentum could be affected by cluster-cluster mergers.

BCGs are distinct galaxies with complex accretion histories, their stellar kinematics and stellar populations reflect their recent mergers and their special connection with their host environment.
In memory of Dr. Gustavo A. Ponce, first inspiration, tutor and friend.
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Thanks for being the most important people in this stage of my life.
Declaration

The work presented in this thesis has been carried out in the Centre for Astrophysics & Supercomputing at Swinburne University of Technology between 2012 and 2015. This thesis contains no material that has been accepted for the award of any other degree or diploma. To the best of my knowledge, this thesis contains no material previously published or written by another author, except where due reference is made in the text of the thesis. The content of the chapters listed below has appeared in refereed journals. Minor alterations have been made to the published papers in order to maintain argument continuity and consistency of spelling and style.

- Chapter 2 has been published as
  *Galaxy and Mass Assembly (GAMA): testing galaxy formation models through the most massive galaxies in the Universe*

- Chapter 3, Appendix A and Appendix B, have been published as
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  *The accretion histories of brightest cluster galaxies from their stellar population gradients*

- Chapter 4 has been submitted for publication to MNRAS.

I performed the analysis and writing of the published work. My co-authors contributed by editing the final manuscript.

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*Melbourne, Victoria, Australia*
*year 2015*
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Introduction

The formation and evolution of galaxies can be broadly explained within the context of the currently accepted paradigm of hierarchical structure formation. In the hierarchical model of structure formation galaxies grow by merging with their neighbours and accreting stars and gas from their surroundings. The brightest and most massive galaxies represent the extreme end of galaxy evolution in this model. Brightest group and cluster galaxies are massive galaxies found at the centres of galaxy groups and clusters. Studying their evolution through different observational techniques unveils processes which help to answer universal questions such as: a) What influences the mass growth in galaxies? b) How do we follow merger imprints in galaxy evolution? c) Do central galaxies evolve differently from non-central galaxies? This Chapter describes our current understanding of galaxy evolution, as an introduction to the research presented in the following Chapters. Each later Chapter will provide specifics on each research project, finishing with the concluding remarks in the last Chapter.

1.1 The current paradigm of galaxy formation and evolution

The hierarchical structure formation model (Toomre 1977; White & Rees 1978) is based on the Λ Cold Dark Matter (ΛCDM) cosmology, which is a parametrisation of the Big Bang model. This model uses General Relativity to explain the formation of large-scale structure. The cosmological constant Λ is a vacuum constant associated with dark energy and the proposed accelerating expansion of the Universe (e.g. Smith et al. 1998; Perlmutter et al. 1999). The ΛCDM model has many successes such as, using only gravity to explain the observed distribution of dark matter in the Universe, as traced by clustering or lensing observations (e.g. Valdarnini 1997; Borgani 1997; Borgani et al. 1997; Katz et al. 1999; Kawata 1999), and predicting the merger history of galaxies (Hopkins et al. 1999).
However, on the scale of galaxies the ΛCDM model is not as successful in predicting their observed properties, due to the effects of baryonic physics, star formation and feedback. This is therefore a major ongoing subject of research.

In the hierarchical structure formation model, galaxy formation and evolution is a bottom-up process. Perturbations in the density of the early Universe give rise to dark matter halos. Gas particles cool in the dark matter halos and coalesce to form stars and eventually galaxies. The galaxies build their stellar mass over time by converting the material accreted from their surroundings into stars as well as by merging with other galaxies. In this hierarchical context, the most massive galaxies represent the extreme of these mass-building processes, they are predicted to have undergone more accretion events than less massive galaxies (e.g. White & Rees, 1978; De Lucia & Blaizot, 2007). Figure 1.1 shows the hierarchical structure formation model of one galaxy.

![Diagram](https://example.com/diagram.png)

Figure 1.1 : Reproduction of Figure 6 in Lacey & Cole (1993). Growth of a halo as a result of a series of mergers (a merger tree). The time (and mass) of the main galaxy increases from top to bottom. The horizontal dashed lines represent the time at which the main galaxy contains 50 percent of its mass (formation time), and 100 percent of its mass (present time). The width of the branches represent the mass of the progenitor galaxies. Massive galaxies are the end product of the merger tree.

The original classification of galaxies, known as the Hubble diagram or tuning fork, was first established at the beginning of the twentieth century by Edwin Hubble (Hubble, 1936). This classification has been continuously tested (see Bernardi et al., 2010, for a summary) since then. The Hubble diagram classifies galaxies based on their morphologies. The most massive and elliptical galaxies in this diagram are called “early-type galaxies”
1.2. Brightest Group and Cluster Galaxies and their role in galaxy evolution

(Figure 1.2) This was based on the comparison of the galaxy spectrum with stellar classifications.

Figure 1.2: Reproduction of Sloan Digital Sky Survey image. Representative early-type galaxy, NGC4365. This massive galaxy is a member of the Virgo cluster.

Galaxy groups and clusters are giant, gravitationally-bound systems of many different types of galaxies (e.g. Hausman & Ostriker, 1978; Beers et al., 1983; Zabludoff et al., 1993). Galaxy groups are systems containing a few to several dozen galaxies (e.g. Huchra & Geller, 1982; Hickson et al., 1992; Magtesyan, 1988; Hickson & Rood, 1988). Galaxy clusters can host hundreds to thousands of galaxies. They have diameters up to 5 Mpc (Noonan, 1980; Jones & Jones, 1980; Sarazin, 1989; Simakov & Shandarin, 1989; Kravtsov & Borgani, 2012) and halo masses greater than $> 10^{14} \, M_\odot$. These are the largest bound systems known in the Universe. They are predicted to have collapsed at early epochs, and therefore they contain the most massive galaxies observed now.

1.2 Brightest Group and Cluster Galaxies and their role in galaxy evolution

Brightest Group and Cluster Galaxies (BCGs) are massive galaxies found at the centres of galaxy groups and clusters. They are some of the most massive galaxies in the Universe, therefore they represent the extreme of galaxy formation. Their properties are a strong test of the hierarchical structure formation model (e.g. De Lucia & Blaizot, 2007; Tonini et al., 2012; Laporte et al., 2013).
In the last decades studies have demonstrated the uniqueness of BCG properties, suggesting that they are different from the rest of the early-type galaxy population (e.g. Matthews et al. 1964; Morgan et al. 1975; Hausman & Ostriker 1978; Bird 1994; Postman & Lauer 1995; Dubinski 1998; Lazzati & Chincarini 1998; von der Linden et al. 2007). Kormendy (1989) argued that galaxies close to the centre of clusters have larger radii and more extended envelopes than other field and cluster galaxies. von der Linden et al. (2007) compared a sample of BCGs from the Sloan Digital Sky Survey (SDSS York et al. 2000) with cluster ellipticals of similar mass. They showed that BCGs have higher velocity dispersions and more extended light profiles (Bernardi et al. 2007). BCGs also have a higher probability of hosting radio-loud active galactic nuclei (AGN; Best et al. 2007).

BCGs are at the peak of the luminosity distribution of the cluster (Bhattacharyya & Basu 1989; Merrifield & Kent 1989; Barnes 1989). However, they are not drawn from a simple extension of the luminosity function, i.e. BCG luminosity functions are distinct from those of other cluster early-type galaxies (e.g. Abell 1964; Loh & Strauss 2006; Wen & Han 2015). Shen et al. (2014) showed that the luminosities of BCGs are systematically brighter than one would infer from the luminosity function of fainter cluster galaxies.

BCGs are clearly different from normal elliptical galaxies and this difference is likely to be a product of their unique environment. Dubinski (1998) used an $N$–body simulation to show that central galaxies are more susceptible to mergers, which naturally lead to higher masses (brighter galaxies).

1.2.1 BCG stellar mass growth

De Lucia & Blaizot (2007) studied the BCG stellar mass growth ratio in a semi-analytic model (SAM). Based on the Millennium simulation (Springel et al. 2005) they predicted a rapid growth in BCG stellar mass with redshift, a factor of 3 since $z = 1$. In contrast, Collins et al. (2009) analysed the stellar mass of X-ray selected BCGs at high redshift ($1.2 < z < 1.5$) and concluded that BCG stellar mass has not changed significantly in the last 9 billion years. Stott et al. (2008) and Stott et al. (2010) found that this result extends over a wider redshift range ($z < 0.8$ and $z > 0.8$, respectively). Whiley et al. (2008) also found a slower BCG stellar mass growth rate since $z \sim 1$ compared to that predicted by SAMs.
More recent studies have now demonstrated that there was an important factor being overlooked: BCG properties depend on their host cluster environment. In particular, the BCG stellar mass correlates with the group/cluster halo mass (Brough et al., 2002, 2008; Lidman et al., 2012). Lidman et al. (2012) analysed the growth of BCGs from 0.1 \( < z < 1.6 \), combining Stott et al. (2008) and Stott et al. (2010)’s data with new photometry from near-infrared imaging of clusters at 0.8 \( < z < 1.6 \), and found that BCGs have grown by a factor of 1.8 over the range 0.1 \( < z < 1.6 \), more consistent with the SAM predictions. However, they have few BCGs at \( z < 0.3 \). Lin et al. (2013) covered a similar redshift range (0 \( < z < 1.5 \)) with a sample from the Spitzer IRAC Shallow Cluster Survey (ISCS) Eisenhardt et al. (2008) in a small cluster mass range, \((2.4–4.5) \times 10^{14} \) M\(_{\odot}\). Their results agree with the SAM predictions at 0.5 \( < z < 1.5 \) where the stellar mass grows by a factor of 2.3, but are still discordant with the SAM predictions at \( z < 0.5 \) (at a 2\( \sigma \) level), where the observed BCGs grow in stellar mass less than 10 percent, in contrast to SAM predictions. There is still tension between the observations and simulations of stellar mass growth in BCGs, particularly at low redshifts.

Observations suggest a merger rate that evolves with time, i.e. a large number of major mergers at high redshifts (\( z > 0.8 \); Lidman et al., 2013; Burke & Collins, 2013; Lin et al., 2013), while at \( z < 0.3 \) major mergers are rarely observed (but not impossible; e.g. Brough et al., 2011). The role of minor merging is less clear (Liu et al., 2009; Edwards & Patton, 2012). Neither the timing (early, \( z > 2 \) or late, \( z < 0.5 \)) of those mergers or whether BCGs really have undergone more mergers than less massive galaxies as predicted by the hierarchical structure formation model has been established, despite a number of studies in this area (e.g. Brough et al., 2002; Whiley et al., 2008; Collins et al., 2009; Stott et al., 2010). Therefore, the mass growth of BCGs (particularly since \( z \sim 0.5 \)) is still an open question.

SAMs suggest that BCGs grow in stellar mass mostly via dissipationless mergers since \( z \sim 1 \). However, some observations have found optical line emission in BCGs at low redshifts (Edwards et al., 2007; O’Dea et al., 2008; Bildfell et al., 2008; O’Dea et al., 2010; Pipino, 2009; Liu et al., 2012; Thom et al., 2012). This line emission indicates a source of ionisation, either Active Galactic Nuclei (AGN) or ongoing star formation (Baldwin, Phillips, & Terlevich, 1981). AGN activity is more common in BCGs than in other cluster galaxies, approximately 30 per cent of BCGs host AGN, in particular Radio-loud AGN (von der Linden et al., 2007; Lin & Mohr, 2007). In contrast, star formation is not as
common in massive galaxies (e.g. Kauffmann et al., 2003, 2004), and therefore is not expected to contribute significantly to the recent stellar mass growth of BCGs. Liu et al. (2012) explored how effective star formation is in building up stellar mass of BCGs, with a large sample of H\textalpha line emitters from the SDSS. They find that the star formation rates are not large enough to contribute to more than 1 per cent of the total stellar mass in the last 2 billion years. Nevertheless, the fraction of AGN and star-forming BCGs in the local Universe has not yet been established, nor the relationship between these fractions and host cluster mass.

1.2.2 BCG position within its host halo

The BCG was traditionally identified as the central galaxy of the host halo. This explained the distinctive properties of these galaxies: if a galaxy lies at the bottom of the dark matter potential well, it will accrete more mass than any satellite (e.g. van den Bosch et al., 2008). The central galaxy grows by cannibalising its neighbours (Dubinski, 1998; Cooray & Milosavljević, 2005) while the satellites experience more violent processes (e.g. ram-pressure and tidal stripping) that prevent them from growing at the same pace. SAMs all assume the BCG to be the central galaxy (De Lucia & Blaizot, 2007). However, observations have debated this assumption (Beers et al., 1983; Zabludo et al., 1993; Lazzati & Chincarini, 1998; Lin & Mohr, 2004; von der Linden et al., 2007; Pimbblet et al., 2006; Coziol et al., 2009; Skibba et al., 2010) showing that BCGs are in some cases outside the core of the group or cluster. To date the properties of the clusters hosting central BCGs compared to those hosting non-central BCGs have not been examined and further studies are needed to determine whether these are different environments.

1.2.3 BCG stellar populations

BCGs are the most massive galaxies in the Universe and as part of groups and clusters, they are predicted to have been formed at early epochs. This would result in old stars and high metallicities (Brough et al., 2007; Loubser et al., 2009). However, their merger histories can affect their initial stellar populations (e.g. Kobayashi, 2004; Hirschmann et al., 2015).

Hydrodynamical simulations show that major mergers are violent events which disrupt stellar population gradients. Dissipationless major mergers mix stars without forming new ones so that gradients appear shallow to flat, $\Delta[Z/H] > -0.3$, $\Delta$Age $< 0.3$, and central stellar populations will be those of the progenitor galaxies (Kobayashi, 2004; Hirschmann, 2015).
Dissipational major mergers trigger star formation in the central region of the remnant galaxy which results in strong negative metallicity gradients $\Delta[Z/H] < -0.3$, positive age gradients $\Delta\text{Age} > 0.3$, and younger ages and higher metallicities in their central stellar populations (Kobayashi 2004; Rupke et al. 2010; Navarro-Gonzalez et al. 2013; Hirschmann et al. 2015). Minor mergers have different effects: the stars of the small galaxy are unlikely to reach the centre, and are added at large radii ($> 2 R_e$). This reinforces stellar population gradients and extends them to the outskirts of the galaxy. Observations have confirmed that minor mergers do not affect central stellar populations (Foster et al. 2009; Barbera et al. 2012; Hilz et al. 2012, 2013; Pastorello et al. 2014).

Given their predicted active dissipationless merger history (De Lucia & Blaizot 2007), BCGs are expected to have shallow metallicity gradients, shallower than lower mass galaxies. However, early observations of BCGs have found a wide range of metallicity gradients. Initially, these gradients were analysed through galaxy colours ($B - V$, $U - V$, $V - R$, $B - R$). The BCGs studied in Wirth & Gallagher (1984), Schombert (1988), Mackie et al. (1990), and Postman & Lauer (1995) showed shallow colour gradients. Using long-slit spectroscopy, Fisher et al. (1996) and Carter et al. (1999) found shallow metallicity gradients in BCGs, however, comparable to the general early-type galaxy population (e.g. Fisher et al. 1996; Kauffmann et al. 1996; Kuntschner 2000; Collobert et al. 2006; Sánchez-Blázquez et al. 2007; Trager et al. 2008; Kuntschner et al. 2010; Thomas et al. 2010). Brough et al. (2007), and Loubser & Sánchez-Blázquez (2012) found a similar range of shallow metallicity gradients, mean $\Delta[Z/H] = -0.28 \pm 0.06$ and mean $\Delta[Z/H] = -0.31 \pm 0.05$, respectively, in their long-slit observations.

Integral Field Spectroscopy (IFS) offers complete spatial coverage of galaxies, hence stellar population gradients can be measured with higher levels of accuracy. Studies of the stellar populations of early-type galaxies from the SAURON and the ATLAS$^{3D}$ team (Kuntschner et al. 2010; McDermid et al. 2015) have shown that early-type galaxies have a wide range of metallicity gradients and these gradients depend on galaxy mass: the more massive the galaxy, the shallower the gradient. They also found that lower mass early-type galaxies are less metal-rich and younger (5 to 10 Gyr) than their massive counterparts ($> 10$ Gyr; Kuntschner et al. 2010; McDermid et al. 2015). To date there are no stellar population analyses of BCGs using IFS and the question of whether BCG show similar evolutionary paths to early-type galaxies remains open.
1.2.4 BCG stellar kinematics

Spectroscopic measurements have shown that the stellar kinematics of galaxies can vary, i.e. some galaxies are rotating while others are nearly static. This classification is made through the stellar kinematic parameters: velocity ($V$) and line-of-sight velocity dispersion ($\sigma$). Simulations have shown that whether the galaxy is rotating or not is directly connected to the galaxy’s recent merger history (e.g. Naab & Burkert 2003; Bournaud et al. 2004; Naab et al. 2006; Cox et al. 2006; Rothberg & Joseph 2006; Jesseit et al. 2009; Hoffman et al. 2010; Tacconi et al. 2010; Khochfar et al. 2011; Bois et al. 2011; Naab et al. 2014; Moody et al. 2014). Several interactions throughout time, can result in fast-rotating or slow-rotating galaxies today. Simulations predict that the most important factor in creating a fast or slow rotators is the relative orientation between the spin of the progenitors and their orbits (e.g. D’Onghia & Burkert 2004), see Figure 1.3.

Using long-slit spectroscopy, Fisher et al. (1995) and Carter et al. (1999) did not find significant rotation in their sample of less than 20 BCGs. Brough et al. (2007) presented the stellar kinematic gradients of 7 BCGs and found no significant gradients in the velocity dispersion. Only one galaxy showed signs of rotation. Later, Loubser et al. (2008) analysed a larger sample of 41 BCGs finding that 2 are fast-rotating BCGs ($>100$ km s$^{-1}$). From these results, BCGs appear to have similar stellar kinematics to normal early-type galaxies where the majority of galaxies are not rotating but some less massive ones are fast-rotating (Davis et al. 1982).

Currently, IFS observations have introduced new comprehensive $V$ and $\sigma$ maps, through which we can observe signs of rotation. The SAURON survey (de Zeeuw et al. 2002) has led the way on this subject, studying the stellar kinematics of 48 early-type galaxies. They proposed the parameter $\lambda_R$ to quantify the specific angular momentum of galaxies (Emsellem et al. 2007). This work has been built upon by the ATLAS$^3$D survey (Cappellari et al. 2011) which has expanded the SAURON sample to 260 galaxies. Through the $\lambda_R$ parameter and the ellipticity of the galaxy, they classify the galaxies as fast rotators (consistent with high angular momentum), and slow rotators (consistent with low angular momentum; Emsellem et al. 2011). These observations have led to the proposal of a new classification of galaxies that not only takes into account their morphology, but also their angular momentum. They found that the most massive and rounded elliptical galaxies are slow rotators, while the less massive, relatively flattened, galaxies are fast rotators (Figure 1.4 Cappellari et al. 2011). This suggests that BCGs should all have low angular
1.2. Brightest Group and Cluster Galaxies and their role in galaxy evolution

momentum (Figure 1.4). Unfortunately, these IFS surveys do not contain many massive galaxies (only 9 with \( M_{\text{dyn}} > 10^{11} \ M_\odot \)). Therefore, this hypothesis has not been confirmed.

Figure 1.3: Reproduction of Figures 2 and 3 from Naab et al. (2014) showing the merger histories of three representative galaxies. The left-hand panels show the galaxy merger histories: number of mergers as a function of redshift. The black bars are major mergers and the orange bars are minor mergers. The central panels are the stellar velocity maps at \( z = 0 \). The galaxy’s name and class are given at the top of the panel, and ellipticity and specific angular momentum at the bottom of the panel. The right-hand panels are the stellar velocity dispersion maps. Naab et al. (2014) presented 6 different classes, which represent different merger scenarios. In this figure three representative classes of those six are shown. Class A is a fast rotator with gas-rich minor mergers and gradual dissipation. Class C is a slow rotator which has had a late gas-rich (\( z \sim 1 \)) major merger. Class F is a round slow rotator whose accretion history is dominated by gas-poor minor mergers. This suggests that a galaxy’s accretion history can be determined from its observed angular momentum.
Figure 1.4: Reproduction of Figure 1 in Cappellari et al. (2011). Morphology of nearby galaxies from the ATLAS$^3D$ parent sample. This image comes from a volume-limited sample of spiral galaxies (70 percent), fast-rotating early-type (25 percent), and slow-rotating early-type galaxies (5 percent). The orange dashed line encloses the final ATLAS$^3D$ sample (only early-type galaxies). The galaxies are presented edge-on and inclined to clearly show the different morphologies. Fast rotators form a parallel sequence with the spiral galaxies, the solid black lines suggest empirical continuity. The dashed black line suggests possible dichotomy. In this scenario, galaxies without a disk, which are more round and massive, are predicted to be slow rotators.

Brough et al. (2011) observed that 1 out of 4 BCGs is fast-rotating (see Figure 1.5) and Jimmy et al. (2013), extending that sample, found that 3 out of 10 are fast rotators. Other studies of individual clusters have observed the angular momentum of the respective BCGs (Emsellem et al., 2014; Scott et al., 2014; Fogarty et al., 2014; Houghton et al., 2013; D’Eugenio et al., 2012). To date the overall fraction of slow-rotating BCGs is $\sim 70$ percent. The reason for the fast or slow rotation in BCGs is still unclear due to the lack of statistically significant samples. There are also no observations of the angular momentum of the central galaxies in groups. Therefore, it is not clear how BCG angular momentum depends on their environment.
1.3 Open questions

The research to date leaves the following open questions:

1. What is the stellar mass growth of BCGs since \( z \sim 0.3 \)?

2. What fraction of BCGs in the local Universe host AGN or star formation activity?

3. Do clusters hosting non-central BCGs have different properties to clusters hosting central BCGs?

4. Are BCG accretion histories different from those of other early-type galaxies?

5. What is the influence of environment on the angular momentum of BCGs?

To address these questions I will use the Galaxy And Mass Assembly (GAMA) survey \cite{Driver_2011}, as well as, IFS observations from VIMOS \cite{Le_Fevre_2003} on the Very Large Telescope and SPIRAL \cite{Sharp_2006} on the Anglo-Australian Telescope.

GAMA\footnote{GAMA: http://www.gama-survey.org/} is a multi-wavelength survey, combining optical spectroscopy, infra-red, optical, UV and radio observations from other connected surveys in five regions of the sky (\( \sim 286 \text{ deg}^2 \)) down to \( r_{\text{petro}} < 19.8 \text{ mag} \) (Figure 1.6). The spectroscopic observations were made at the 3.9m Anglo-Australian Telescope and are now complete with \( \sim 300,000 \) galaxies in...
Chapter 1. Introduction

the survey and a spectroscopic completeness of $\sim 97$ percent (Driver et al., 2011; Hopkins et al., 2013; Liske et al., 2015). This survey provides a range of derived information such as group membership (Robotham et al., 2011), galaxy stellar mass (Taylor et al., 2011) and emission line (Gunawardhana et al., 2013) properties. The high spectroscopic completeness, specifically for close pairs of galaxies, and wide photometric and spectroscopic information, ensures that GAMA is the ideal survey with which to analyse BCG properties.

GAMA observations cover a wide range of group halo masses ($10^{12} < M_{\text{halo}} [M_\odot] < 10^{15.5}$) and galaxy stellar masses ($10^8 < M_\star [M_\odot] < 10^{12.5}$) in the redshift range $0 < z < 0.3$. I use these observations to study the evolution of BCGs from a complete, homogeneous, volume-limited sample. I analyse the BCG stellar mass growth in the last 3 billion years, as well as, their halo position, star formation and AGN activity (Questions 1, 2, and 3).

Figure 1.6: Reproduction of Figure 1 in Driver et al. (2011). Sky regions covered by different surveys. GAMA phase I (used in this thesis) is highlighted by thick black regions, SDSS (also used in this thesis) is shown by orange circles.
To study the spatially-resolved stellar populations and kinematics of BCGs for the first time, I use VIMOS and SPIRAL IFS observations. VIMOS and SPIRAL both have large fields-of-view (VIMOS: 27 arcsec × 27 arcsec, SPIRAL: 11.2 arcsec × 22.4 arcsec) which allow good spatial coverage of the galaxies. They also provide moderate spectroscopic resolution (R~ 1500), which allow us to resolve the stellar populations and kinematics. The samples cover central galaxies in groups (BGGs), as well as in clusters (BCGs). I compare the BCG recent accretion histories to those of the early-type galaxies observed by the ATLAS$^{3D}$ survey (Question 4). I also present the first analysis of the influence of environment on BCG angular momentum (Question 5). The range of halo masses are crucial to constrain the effect of halo masses of the angular momentum of BCGs.
1.4 Thesis outline

This thesis studies the properties of brightest group and cluster galaxies (BCGs). These are unique galaxies which push the hierarchical structure formation model to its limits. Their extreme masses and privileged location at the centres of groups and clusters are a challenge for observations and simulations. Here I describe the analyses developed around the open questions presented in Section 1.3. The different methodologies are explained in each Chapter.

Chapter 2 presents the statistical analysis of 883 BCGs at $z < 0.3$ selected from the GAMA survey (Driver et al., 2011). It details the sample selection, the survey and the data used in the analysis. BCG stellar mass growth in the last 3 billion years, star formation and AGN activity and position in their host halo are analysed here. This Chapter addresses Questions 1, 2 and 3 of Section 1.3.

Chapter 3 presents the spatially-resolved stellar population analysis of 10 BCGs observed with the VIMOS IFS on the Very Large Telescope. These galaxies were kinematically classified in Jimmy et al. (2013). This Chapter describes the sample selection, observation, the full-spectrum fitting technique used in the analysis and the final results. It addresses Question 4 in Section 1.3.

Chapter 4 focuses on the influence of environment on the angular momentum of central BCGs. The sample expands that of Jimmy et al. (2013) by adding 12 galaxies selected from GAMA and SDSS and observed with the SPIRAL IFS on the Australian Astronomical Observatory. This Chapter outlines the sample selection, observations, and stellar kinematic analysis. The influence of environment is studied through the stellar mass - halo mass relationship and the difference in magnitude between the two brightest galaxies in the host halo. The results address Question 5 from Section 1.3.

Chapter 5 summarises the results of the previous Chapters with a wider discussion bringing the results together in a final conclusion. The Chapter later presents the open questions raised from the results presented in this thesis, along with a brief overview of the future of BCG observations.

The cosmology adopted throughout this thesis is $H_0=70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M=0.3$, $\Omega_{\Lambda}=0.7$. 
BGG/BCG stellar mass growth since $z = 0.3$: a comparison with theoretical models

This Chapter analyses the growth of brightest group and cluster galaxies over the last 3 billion years using a large sample of 883 galaxies from the Galaxy And Mass Assembly survey. The method implemented here compares the mass of local BGG/BCGs with the stellar mass of their potential progenitors at $0.17 < z < 0.3$. The Chapter also includes the statistical analysis of Hα line emission in these galaxies, as a proxy of star formation or AGN activity, as well as, a comparison between the properties of clusters hosting central BGG/BCGs with clusters hosting non-central BGG/BCGs. The discussion covers the role of star formation, galaxy mergers, and BGG/BCG position on the growth of the BCG.


2.1 Introduction

In the hierarchical model of structure formation, galaxies grow in size and stellar mass by accreting other galaxies and material from their surroundings. The brightest group and cluster galaxies (hereafter BGGs and BCGs) are the most extreme examples of this process and the most luminous objects known at the present epoch.

N-body simulations accurately describe how the dark matter halos evolve in the hierarchical formation model scenario, however, they are unable to simulate in detail the processes that lead to galaxy evolution. Halo abundance-matching (dark-matter-only using a statistical model constrained by observations) simulations and semi-analytical models (SAM) are two approaches that are commonly used in the literature. Halo abundance-matching models follow the behaviour of the ΛCDM cosmology with gravity (e.g. Moster et al.)
Chapter 2. BGG/BCG stellar mass growth since $z = 0.3$

SAMs (e.g. De Lucia & Blaizot 2007, Tonini et al. 2012) are a combination of N-body simulations and analytic descriptions of galaxy formation physics (i.e. star formation, dust extinction, AGN feedback, etc; for a review see Mutch et al. 2012). BCGs are particularly difficult to reproduce using these models, with their photometric colours tending to be bluer compared to observations, and their masses overestimated (Bower et al. 2006, Croton 2006, De Lucia & Blaizot 2007, Collins et al. 2009, Silk & Mamon 2012).

There are few models that focus solely on BGGs and BCGs. Among them De Lucia & Blaizot (2007) who used the Millennium N-body simulation of Springel et al. (2005) to model the development of BCGs over cosmic time. A similar approach was used by Tonini et al. (2012). More recently, Moster et al. (2013) introduced an abundance-matching simulation of galaxy groups and clusters, using a statistical model constrained by observations. However, these simulations have not yet converged with observations. Despite these efforts, the assembly history and evolution of BGGs and BCGs is still poorly understood. SAMs and abundance-matching simulations predict a factor of three increase in the BCG stellar mass since $z = 1$. On the other hand, earlier observational studies implied a very different result, arguing that BCG stellar masses 9 billion years ago were not very different to their stellar masses now (Baugh et al. 1999, Whiley et al. 2008, Stott et al. 2008, 2010, Collins et al. 2009).

Recently, Lidman et al. (2012) show that from $0.1 < z < 0.9$, BCGs grow in mass by a factor of $1.8 \pm 0.3$. This is in closer agreement with the predictions from SAMs (De Lucia & Blaizot 2007, Tonini et al. 2012). Also Lin et al. (2013), found remarkably good agreement with the SAM of Guo et al. (2011) over the redshift interval $0.5 < z < 1.5$ (growth by a factor of 2.3). However, below $z = 0.5$, they found that the growth stalls, a result that is not seen in the models. This Chapter will examine this low redshift interval more closely ($0.09 < z < 0.27$).

Another important prediction made by hierarchical formation models is that BCGs are assembling their mass through similar mass mergers with little gas present (De Lucia & Blaizot 2007, Laporte et al. 2013). However, recent analyses have shown that some BCGs harbour on-going star formation (Edwards et al. 2007, O’Dea et al. 2008, 2010, Pipino 2009, Liu et al. 2012, Thom et al. 2012). Liu et al. (2012), with an optical sample selected from the Sloan Digital Sky Survey (SDSS; York et al. 2000), found that the star formation
rate in BCGs is not always low, although it is not high enough to increase the stellar mass of the BCG by more than 1 per cent over the last 2 billion years. The existence of star formation in such old galaxies has important implications for simulations (Tonini et al., 2012).

The position of the brightest galaxy in a group or cluster has been broadly studied in the last decades. The BGG/BCG was traditionally identified as the central galaxy of the host halo. Lately observations have debated this assumption (Beers et al., 1983; Postman & Lauer, 1995; Lin & Mohr, 2004; Pimbblet et al., 2006; von der Linden et al., 2007; Bildfell et al., 2008; Hwang & Lee, 2008; Sanderson et al., 2009; Coziol et al., 2009; Skibba et al., 2010) showing that BGG/BCGs in some cases are outside the core of the group or cluster. The proposed explanation for this is ongoing halo merging. Observationally, this can be understood as different stages in the hierarchical clustering process (Pimbblet, 2008; Brough et al., 2008).

SAMs assume the BGG/BCG to be the central galaxy in their simulations (e.g. De Lucia & Blaizot, 2007). This could give biased results on the accretion history of the BCG. Other have set the central galaxy at the minimum of the potential well of the cluster (Croton, 2006; Guo et al., 2011). When the cluster contains substructures, the minimum of the potential well could be away from the centre. Martel et al. (2014) ran an $N$-body cosmological simulation of 1788 groups and clusters with $M_{\text{cl}} > 10^{12} M_\odot$. They found that the fraction of halos with off-centre BGG/BCGs increases with increasing halo mass (from 0 to 0.2). However, they do not claim this trend to be definitive since the lower mass systems can be biased by the magnitude cut they use to select their galaxies. They confirm the observations, showing evidence of how major cluster-cluster mergers can affect the brightest galaxy position.

This Chapter analyses a sample of BGG/BCGs selected from the Galaxy And Mass Assembly survey (GAMA; Driver et al., 2011). This sample is one of the largest available to date, covering a wide range of halo mass ($10^{12} - 10^{15} M_\odot$). Throughout this Chapter groups are separated from clusters by a halo mass cut of $M_{\text{halo}} = 10^{14} M_\odot$.

This analysis focuses on the BGG and BCG stellar mass growth spanning $0.09 \leq z \leq 0.27$, and the comparison of the results with the galaxy formation and evolution models of De Lucia & Blaizot (2007), Tonini et al. (2012), Laporte et al. (2013) and Moster et al. (2013).

1The analysis was tested by separating groups from clusters through multiplicity, and the results are consistent.
In addition, it quantifies the active galactic nucleus (AGN) and star formation (SF) activity within these galaxies, and explores the impact of ongoing star formation on the growth of these giant galaxies. The analysis also compares the properties of BGG/BCGs that are not at the centre of the potential well with those that are, looking for correlations between the properties of BGG/BCGs and the properties of the dark matter halos in which they live.

2.2 The Galaxy And Mass Assembly (GAMA) survey

The Galaxy And Mass Assembly (GAMA) survey is a multi-wavelength galaxy survey (Driver et al., 2011). Beginning in 2008 it has obtained optical spectra from the 3.9m Anglo-Australian Telescope (AAT) in five regions of the sky covering 290 deg$^2$. GAMA I contains three of these regions ($\sim$ 144 deg$^2$). The galaxies analysed here were specifically selected from this first phase of the survey (Driver et al., 2011). There are $\sim$ 170,000 galaxies in the GAMA I sample, down to $r \sim 19.4$ mag in two regions each of 48 deg$^2$ and $r \sim 19.8$ mag in a third region also of 48 deg$^2$. GAMA has a very high spectroscopic completeness (on average 97 per cent; Driver et al., 2011). This has been achieved by returning to each target area an average of 10 times (Robotham et al., 2010). Sloan Digital Sky Survey (SDSS; York et al., 2000) imaging has also been re-analysed for GAMA targets (Hill et al., 2011; Kelvin et al., 2012), and stellar mass determinations have been made from spectral energy distributions (Taylor et al., 2011). The spectra enable measurement of emission line star formation rates (SFR) form optical spectra (Hopkins et al., 2013; Gunawardhana et al., 2013). This work includes those targets having reliable redshifts, i.e. quality value $nQ \geq 3$ (Baldry et al., 2010; Hopkins et al., 2013).

2.2.1 The GAMA Galaxy Group Catalogue (G$^3$C)

A full description of the GAMA Galaxy Group Catalogue (G$^3$C) can be found in Robotham et al. (2011). Here I use version v04 of the group catalogue. The groups in this catalogue were identified with an adaptive friends-of-friends algorithm, tested with mock GAMA light-cones. These GAMA light-cones have been constructed from the millennium ACDM N-body simulations (Springel et al., 2005) using the galaxy formation SAM of Bower et al. (2006). In order to simulate realistic GAMA galaxies, the mock catalogues include the limitations of GAMA spectroscopy. G$^3$C comprises 14,388 galaxy groups with multiplicity $\geq 2$ containing 44,186 galaxies. This represents 40 per cent of the galaxies in GAMA. To prevent confusion, henceforth, all groups and clusters will be referred to as ‘halos’ in
the cases where distinction is not necessary.

The methods to measure the halo properties in the G$^3$C were selected in order to be robust and unbiased to perturbations even in groups with a small number of members. This was achieved by comparison with the mock catalogues.

It is crucial for this analysis to identify the BGG/BCG and the halo centre. In the group catalogue, the BCG is simply defined as the brightest (most luminous) galaxy within the half group radius, $R_{50}$, in the absolute $r_{AB}$ luminosity.

To find the most suitable halo centre three definitions were tested by Robotham et al. (2011): the centre of the total light of the halo (CoL), the iterative centre of light, and the brightest halo galaxy. The CoL comes from the mean position of all galaxies weighted by flat $r_{AB}$ luminosity. The iterative centre of light comes from multiple iterations on the halo $r_{AB}$ luminosity. For each iteration the centroid of the halo $r_{AB}$ luminosity is found, rejecting the distant galaxies and selecting the brightest from the remaining ones. The central position is assigned to the galaxy closest to the centroid of the overall light distribution of the system. The iterative centre of light was found to be the most robust definition from comparison with mock halos. This method produces a perfectly recovered centre position (within 3.5 kpc) between observations and mocks 90 per cent of the time. This is significantly higher than \(~\approx~70\) per cent of matches for the BGG/BCG centre, and 20 per cent for the CoL method respectively. The iterative centre was also shown to be less sensitive to perturbations by individual members, and very stable as a function of multiplicity. For multiplicities $5 \leq N \leq 19$, the observed systems recover the position in the mock catalogues in \(~\approx88\) per cent of the cases. The stability increases slightly for $N > 19$ (to 93 per cent).

The halo velocity dispersion ($\sigma_{\text{halo}}$) is directly affected by group multiplicity, survey completeness, and the survey magnitude limits. In order to obtain unbiased halo velocity dispersions, Robotham et al. (2011) examine the robustness of the halo identification algorithm. The galaxies within a halo are identified using a friends-of-friends algorithm based on the luminosity function of the survey and linking parameters selected using the mock survey light cones. The linking parameters include a correction for spectroscopic incompleteness. The correction slightly increases the linking length to account for missing nearby galaxies. However, GAMA has a high spectroscopic completeness (\(~\approx97\) percent)
which means that this correction is minor. On average \( \sim 1 \) percent of the linking length.

The efficiency of the group identification is tested bijectively by comparing the group catalogue with the mock catalogue and vice-versa. This efficiency (\( S_{tot} \)) in Robotham et al. (2011) is directly proportional to the group multiplicity, on average this efficiency is \( \sim 40 \) percent which is considered reliable.

Once the groups are reliably identified, the halo velocity dispersion is measured with the method introduced by Beers et al. (1990). This method is unbiased even for low multiplicity groups. The halo velocity dispersion is calculated from the gaps between each galaxy pair in velocity as follows:

\[
\sigma_{\text{halo}} = \sqrt{(N/(N-1))\sigma_{\text{gap}}^2 - \sigma_{\text{err}}^2}
\]

where \( N \) is the multiplicity of the group, \( \sigma_{\text{gap}} \) is the recession velocity gap and \( \sigma_{\text{err}} \) is the summation of the velocity uncertainty from all the galaxy. For GAMA the mean velocity uncertainty is \( \sim 50 \) km s\(^{-1}\). The recovered halo velocity dispersion for 80 percent of the groups with multiplicity \( > 5 \) is within the 50 percent of the intrinsic value (Figure 2 in Robotham et al. 2011). The distribution of the group multiplicity and halo velocity dispersions are shown in Figures 2.1 and 2.2. Figure 2.3 shows the group multiplicity as a function of its velocity dispersion.

The mean multiplicity of the groups in the sample is 8.73 \( \pm \) 9.37. Which means that the sample is dominated by poor groups. However, the velocity uncertainties are homogeneous as function of multiplicity. The mean velocity dispersion uncertainty for groups of multiplicity \( 5 < N < 15 \) is 47 km s\(^{-1}\) \( \pm \) 4.18. While the mean velocity dispersion uncertainty for groups of multiplicity \( > 15 \) is 47 km s\(^{-1}\) \( \pm \) 3.15. Therefore, the effect of multiplicity upon the final results are minor.

The dynamical mass (\( M_{\text{halo}} \)) is proportional to \( A\sigma_{\text{halo}}^2 R_{50} \) (from the virial theorem). \( A \) is proportional to \( A \sim (M_{DM}/M_{\text{FoF}}) + (1/\sqrt{N}) \) where \( M_{DM} \) is the mass of the dark matter halo extracted from the Millennium simulation (not dependent on the details of the semi-analytic models), and \( M_{\text{FoF}} \) is the mass of the group with members identified through friends-of-friend algorithm. This scaling factor leads to a median unbiased mass estimate.

The uncertainties in calculating the dynamical mass were tested through density dis-
2.2. The Galaxy And Mass Assembly (GAMA) survey

tributions ($\log \sigma_{\text{FoF}}^2 / \sigma_{\text{DM}}^2 = \log \text{Rad}_{50-\text{FoF}} / \text{Rad}_{50-\text{DM}}$). The dynamical mass was shown to be more consistent in halos with multiplicities $N \geq 5$ since the radius is recovered more accurately in those cases. Therefore, this analysis is limited to BGG/BCGs in halos with multiplicity $N \geq 5$ (mean $N = 8.73 \pm 9.37$), resulting in 1220 halos (i.e. 1220 BGG/BCGs, $10^{12} \text{M}_\odot < M_{\text{halo}} < 10^{15} \text{M}_\odot$). The scaling factor in these cases were shown to be $A = 10$ from a global optimisation of the match between the friends-of-friends groups and the mock catalogues.

In addition to the properties described above, the parameters: modality, dominance and relative over-density are also used as part of the analysis. The modality describes the Gaussianity of the velocity dispersion distribution in the halo, and is defined as $(1+\text{skewness}^2)/(3+\text{kurtosis}^2)$. For Gaussian systems it is close to 1/3. The dominance is defined as the luminosity gap between the BGG/BCG and the second brightest galaxy in a halo ($\Delta m_{1,2}$). The magnitudes used are apparent $r_{\text{AB}}$ band magnitudes from SDSS. Finally the relative halo overdensity is a measure of how isolated the group is relative to larger scale structures. It is calculated by detecting the number of objects within a comoving cylinder of radius $1.5 h^{-1}\text{Mpc}$ and radial depth of $36 h^{-1}\text{Mpc}$ centred at the centre of the halo.

![Figure 2.1](image.png)

Figure 2.1: Group multiplicity distribution ($N \geq 5$). The majority are groups with less than 20 group members (mean $N = 8.73 \pm 9.37$).
Figure 2.2: Halo velocity dispersion distribution (mean $\sigma_{\text{halo}} = 305.47 \pm 160$).

Figure 2.3: Group multiplicity as a function of halo velocity dispersion. On average, groups with more members have higher velocity dispersion.
2.2.2 GAMA Stellar Mass Catalogue

The stellar masses ($M_*$) for all GAMA galaxies are calculated as described in Taylor et al. (2011). Here catalogue version v08 is used. The stellar mass estimates were derived by fitting the Spectral Energy Distributions (SEDs; Bruzual & Charlot 2003, BC03) to SDSS (York et al., 2000) $ugriz$ imaging reprocessed by the GAMA team (Hill et al., 2011). The dust obscuration law applied was that of Calzetti et al. (2000), and a Chabrier (2003) initial mass function (IMF) was assumed. To account for aperture effects, a correction based on the Sérsic fit to the surface brightness profiles is applied to the stellar masses (see Taylor et al., 2011; Kelvin et al., 2012).

GAMA I galaxies have stellar masses ranging from $3 \times 10^7$ to $3 \times 10^{12} M_\odot$; this is illustrated in Figure 2.4 by the grey dots. The stellar masses of the sample of 1220 BCGs are between $1 \times 10^9$ and $3 \times 10^{12} M_\odot$, also shown in Figure 2.4 as black circles, these BCGs live in halos with $N \geq 5$. To ensure that the sample is not biased by mass-dependent selection effects, a volume-limited sample is selected, with a stellar mass limit $3 \times 10^{10} M_\odot$ over $0.09 < z < 0.27$ (blue circles within the box in Figure 2.4). This final sample contains 883 halos (i.e. 883 BGG/BCGs).

2.2.3 GAMA Emission Line catalogue

GAMA spectra were obtained using the AAOmega multi-object spectrograph (Sharp et al., 2006) which has a 2” fibre. The targets were observed with the 580V and 385R AAOmega gratings giving an observed wavelength range of $\sim 3700$-8900 Å with a spectral resolution of 3.2 Å FWHM. The spectra are extracted, flat-fielded and wavelength and flux-calibrated as described in Hopkins et al. (2013). The galaxies in this sample represent the brightest galaxies in the GAMA survey. Their emission-line measurements are taken from the SDSS (MPA-JHU DR7 data base, Brinchmann et al., 2004, Tremonti et al., 2004). These flux measurements have been corrected for stellar absorption using a library of single stellar population models (Bruzual & Charlot, 2003). The best fit to the continuum of the observed spectrum is subtracted as well as any remaining residuals. Spectral line measurements are made assuming a single Gaussian approximation fitted from a common redshift value and line-width within adjacent sets of lines.

The galaxies are classified as Active Galactic Nuclei (AGN) and Star Forming (SF) galaxies using the division described by Kewley et al. (2001) in the Baldwin, Phillips, & Terlevich (BPT: 1981) diagram. This division is based on the $[N_{\text{II}}]/H\alpha$ and $[O_{\text{III}}]/H\beta$ line ratios,
Chapter 2. BGG/BCG stellar mass growth since $z = 0.3$

Figure 2.4: BGG/BCGs in the GAMA sample. Stellar mass as function of redshift, $z$. The stellar mass of GAMA I galaxies as a function of redshift is shown as grey dots. The $M_*$ threshold is a function of $z$. Galaxies in black are the BGG/BCGs from halos with multiplicity greater than or equal to 5. The BGG/BCGs in blue delimited by the blue box, are the final sample of 883 BCGs, they are taken from halos with multiplicity $N \geq 5$ at redshifts $0.09 < z < 0.27$ and with $M_* \geq 3 \times 10^{10} \, M_\odot$.

shown in Figure 2.5. If measurements for all four lines are not available then the two-line diagnostic given by Kewley et al. (2001) was used, and if measurements for two lines are not available then the galaxy was classified as uncertain (Gunawardhana et al., 2013). The line flux measurements are not corrected for aperture effects. However this does not biased the AGN/SF classification, since AGN/SF activity in BCGs generally happens at the central regions of the galaxies. In the redshift range covered by our sample, the central region of these galaxies fit within the aperture of the fibre used by the GAMA survey ($2''$).

The calculation of the star formation rates (SFR) is described in Gunawardhana et al. (2013) and the catalogue version used here is v04.10. SFRs are calculated from the corrected Hα luminosities using the relationship defined by Kennicutt (1998). This uses a Salpeter (1955) initial mass function (IMF), translated here to Chabrier (2003) IMF to be consistent with the stellar mass catalogue (using the relationship given by Baldry & Glazebrook 2003). The GAMA Hα flux limit is $2.5 \times 10^{-16}\text{ergs}^{-1}\text{cm}^{-2}$ which cor-
responds to a SFR of $0.1 \text{M}_\odot\text{yr}^{-1}$ at $z = 0.27$. This is the threshold to recognize H$\alpha$ as an emission line. Therefore in this sample the star-forming galaxies are those with $0.1 < \text{SFR} \leq 100 \text{M}_\odot\text{yr}^{-1}$. Any measurement higher than $100 \text{M}_\odot\text{yr}^{-1}$ is potentially unreliable. Galaxies affected by sky lines lying at the same wavelength as the emission lines were excluded from the final sample.

The SFR measurements are derived from the integrated flux of the whole galaxy. They have been corrected for stellar absorption and aperture effects in the 2" GAMA fibre spectra. The stellar absorption and aperture effect corrections are described in Gunawardhana et al. (2013), following Hopkins et al. (2003). Less than 10 percent of the GAMA sample is significantly affected by stellar absorption. To account for aperture effects GAMA uses the $r$-band magnitude to approximate the continuum at the H$\alpha$ region. The correction includes this magnitude and a factor that varies with $z$. On average the required correction is a factor of 2-4.

Figure 2.5 : BPT digram. The BGGs and BCGs are shown as grey crosses if they present AGN activity, and as black circles if they are star-forming. The solid line indicates the distinction between AGN and star-forming galaxies defined by Kewley et al. (2001).
2.3 BCG Stellar Mass–Halo Mass Relationship

There is a known correlation between the stellar mass of the BCG and the mass of its host dark matter halo. The more massive the halo, the more massive the BCG. Many studies (e.g. Brough et al., 2005, 2008; Stott et al., 2008; Whiley et al., 2008; Stott et al., 2010, 2012; Collins et al., 2009; Hansen et al., 2009; Lidman et al., 2012) have explored the slope of this $M_\ast - M_{\text{halo}}$ correlation and have found it to be less than unity. This implies that the galaxy does not grow at the same rate as the cluster; the cluster acquires its mass faster than the BCG.

To study the $M_\ast - M_{\text{halo}}$ relationship for the galaxies in this sample, the best fit is determined using Bayesian statistics. The data are treated as a 2D Gaussian with uncertainties in both variables, taking into account the intrinsic scatter. I generate a flat prior (uniform values, no uncertainties), to later maximised it (likelihood) through Markov Chain Monte-Carlo (MCMC) iterations. From the maximum posterior distribution the index of the power-law (hereafter referred as $b$ and $M_\ast \propto M_{\text{halo}}^b$) is found to be $b = 0.32 \pm 0.09$. The uncertainty is the standard deviation of the MCMC iterations. The result is robust to flipping the axes. The goodness of the fit is tested through the efficiency of the MCMC implementation (Foreman-Mackey et al. 2012). Figure 2.6 shows the best fit for the $M_\ast - M_{\text{halo}}$ relationship as a solid line. The 883 BCGs are divided into two redshift bins that are represented in this Figure by different colours. The low-redshift sample ($0.09 \leq z \leq 0.17$) is shown as green points, and the high-redshift sample ($0.17 < z \leq 0.27$) as purple crosses. The blue error bars represent the median errors for each of the $M_\ast$ and $M_{\text{halo}}$ bins. The power-law index of $\sim 0.32$ implies that if the halo grows by a factor of 10 in dynamical mass, its BGG or BCG only gains a factor of two in stellar mass.

As a further analysis, the $M_\ast - M_{\text{halo}}$ relationship for the different subsamples: (i) low vs high redshift, and (ii) groups vs clusters separated at $M_{\text{halo}} = 10^{14} M_\odot$. The power-law indexes for the low-redshift sample ($b = 0.33 \pm 0.21$), and high-redshift sample ($b = 0.30 \pm 0.20$) are consistent within the error bars, while the differences between groups and clusters is more apparent. The relationship is shallower for the groups than for the clusters, $b = 0.19 \pm 0.20$, and $b = 0.39 \pm 0.16$ respectively. However, the relationships of the groups and clusters are still consistent within the error bars. In conclusion, there is no significant change in the BGG/BCG stellar mass – host halo mass relationship as a function of redshift or halo mass.
Comparing the index of the power-law to previous analyses good agreement is found with the analyses at similar redshift range, e.g. [Hansen et al. (2009)] who explored this $M_\ast - M_{\text{halo}}$ relationship for BCGs at $0.1 < z < 0.3$. Whiley et al., (2008) also found a correlation between $k$-band luminosity and cluster velocity dispersion in a wider redshift range ($0.2 < z < 1$). They state that this correlation although significant, is rather weak. The BCG grows $\sim 70$ percent while the cluster grows two orders of magnitude. The model of [Moster et al. (2013)] suggest an evolution of the $M_\ast - M_{\text{halo}}$ relationship with redshift. However, observations do not show such a trend yet ([Brough et al. 2008] Whiley et al. 2008).

Figure 2.6: BCG Stellar Mass – Host Halo Mass relationship. BGG/BCGs at low-redshift ($0.09 \leq z \leq 0.17$) are shown as green circles and those at high-redshift ($0.17 < z \leq 0.27$) are shown as purple crosses. The best-fit relationship determined through a Bayesian approach ($M_\ast \propto M_{\text{halo}}^{0.32\pm0.09}$) is shown by the solid black line. The median $M_{\text{halo}}$ and BCG $M_\ast$ error bars in bins of halo mass are plotted at the bottom of the figure. BGG/BCG stellar mass and host halo mass are correlated such that the halo grows faster than the BGG/BCG.

### 2.4 BCG growth in the last 3 billion years

This study intends to measure the growth of BCGs in the last 3 billion years. This is achieved by comparing the high-redshift sample with the low-redshift sample. In order to have a reliable comparison between galaxies at higher redshifts and their likely descen-
Chapter 2. BGG/BCG stellar mass growth since $z = 0.3$

It is necessary to be sure that the growth in halos is taken into account. Here the approach implemented in Lidman et al. (2012) is used, as described below.

The halos have been observed at different redshifts so they cannot be compared directly with each other, e.g. halo A at $z = 0.25$ is not comparable with halo B observed at $z = 0.1$. The same halo A observed later at $z = 0.1$ would be very different (larger and more massive). Therefore, the first step is to evolve all the halos in time to a common redshift, $z = 0$, to find the mass that the cluster will likely have by the present day. For this the median accretion rate from the model of Fakhouri, Ma, & Boylan-Kolchin (2010) is used. This model is consistent with other hierarchical structure formation models (Wechsler et al., 2002).

As well as the halos, BCGs differ depending on the redshift at which they are observed. The main interest is to measure their growth in stellar mass due to mergers and starburst phenomena, but galaxies also lose material with time due to stellar winds and supernova explosions (mass loss due to stellar evolution). Here (as shown in Lidman et al. 2012), this mass loss is accounted for using the stellar population model of Bruzual & Charlot (2003). Since the redshift range only extends to $z = 0.27$, the effect of the stellar mass loss is minimal ($\sim 0.05$ dex). Table 2.1 shows the median values of the evolved $M_{\text{halo}}$ and $M_*$, as well as the $M_{\text{halo}}$ and $M_*$ values at the observed redshift.

After evolving the mass of each halo to the same redshift, a set range of halo masses can be selected, and the stellar masses of the BGGs and BCGs from the high and low-redshift samples can be compared, having already been corrected for the mass loss by passive evolution. For this the $M_{\text{halo}}$ distribution of each redshift sample is examined. The left-hand panels of Figure 2.7 and 2.8 show the distributions of the evolved $M_{\text{halo}}$ values in each redshift sample for groups and clusters respectively. Note that the distributions vary from one to another: different sample sizes, skewness, and medians. In order to compare the stellar masses of like-mass halos all the groups and clusters from the high-$z$ and low-$z$ samples with similar halo masses are selected. The new subsamples are shown in the right-hand panels of Figure 2.7 and 2.8. They now have the same distributions. This implies that the halos in the high redshift subsample are likely to be the “progenitors” of the halos in the low redshift subsample.

To estimate the $M_*$ growth over the last 3 billion years the median BGG and BCG $M_*$
corresponding to the $M_{\text{halo}}$ matched subsamples is calculated. The final $M_*$ distributions are shown in Figure 2.9. The left-hand panels are the groups. The right-hand panels are the clusters. The medians are shown in Table 2.2. The final $M_*$ growth is given by the ratio of the low-$z$ median $M_*$ to the high-$z$ median $M_*$. The errors are calculated by bootstrap-resampling of the subsamples. No statistically significant growth in the last 3 billion years is found. The $M_*$ ratio for BGGs and BCGs is 1 within the error bars ($0.92 \pm 0.07$ for the groups, $0.93 \pm 0.09$ for the clusters). This result is in agreement with Lin et al. (2013), who found that the BCGs acquire less than 10 per cent stellar mass between $0 < z < 0.5$.

Table 2.1: Median values of the whole sample per redshift bin.

<table>
<thead>
<tr>
<th>Redshift bin$^a$</th>
<th>log $M_{\text{halo}}$ [M$_\odot$] at observed $z$</th>
<th>log $M_{\text{halo}}$ [M$_\odot$] at $z = 0^b$</th>
<th>log $M_*$ [M$_\odot$] at observed $z$</th>
<th>log $M_*$ [M$_\odot$] at $z = 0^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-$z$ (0.17 &lt; $z$ ≤ 0.27)</td>
<td>13.83</td>
<td>13.93</td>
<td>11.293</td>
<td>11.286</td>
</tr>
<tr>
<td>Low-$z$ (0.09 ≤ $z$ ≤ 0.17)</td>
<td>13.57</td>
<td>13.63</td>
<td>11.174</td>
<td>11.169</td>
</tr>
</tbody>
</table>

$^a$ Both redshift samples (High-$z$ and Low-$z$) are the same size: 441 BCGs.
$^b$ BCG $M_*$ are corrected for passive evolution, and $M_{\text{halo}}$ are corrected to the mass they are likely to have at $z = 0$.

Table 2.2: Median BGG/BCG $M_*$ per redshift sample corresponding to the matched $M_{\text{halo}}$ groups and clusters.

<table>
<thead>
<tr>
<th>Redshift bin</th>
<th>Median $z$</th>
<th>log $M_*$ [M$_\odot$]</th>
<th>log $M_*$ [M$_\odot$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-$z$ (0.17 &lt; $z$ ≤ 0.27)</td>
<td>0.136</td>
<td>11.183</td>
<td>11.343</td>
</tr>
<tr>
<td>Low-$z$ (0.09 ≤ $z$ ≤ 0.17)</td>
<td>0.214</td>
<td>11.142</td>
<td>11.291</td>
</tr>
</tbody>
</table>

2.5 AGN and Star formation activity

H$\alpha$ in emission is indicative of star formation and/or AGN activity. To discriminate between the two ionisation sources, the Baldwin, Phillips, & Terlevich (1981) diagram described by Kewley et al. (2001, see Section 2.2.3) is used. In previous studies, it has been shown that a large fraction (about 30 per cent overall) of BCGs have signatures of AGN activity, including radio emission (von der Linden et al., 2007; Lin & Mohr, 2007; Stott et al., 2012). BCGs are most likely to be in high density environments and comprise
Chapter 2. BGG/BCG stellar mass growth since \(z = 0.3\)

Figure 2.7: Histograms of group halo mass evolved to the present epoch for low (upper panel; \(0.09 \leq z \leq 0.17\)) and high redshift (lower panel; \(0.17 < z \leq 0.27\)) samples. **Left-hand panels:** \(M_{\text{halo}}\) distribution (mass evolved to present epochs) for the whole sample per redshift bin. The differences in the median halo masses are illustrated by the dotted lines. **Right-hand panels:** Matched histograms after selecting the groups, from the high-\(z\) and low-\(z\) samples, with similar halo masses. Each subsample contains 127 groups, i.e. 127 BGGs. A halo mass like for like comparison is guaranteed between the two different redshift bins.

Old stellar populations. Star formation is not predominant in these galaxies, although it does rarely occur [Kauffmann et al., 2003, 2004; Edwards et al., 2007; O’Dea et al., 2008; Bildfell et al., 2008; O’Dea et al., 2010; Pipino, 2009; Liu et al., 2012; Thom et al., 2012]. Liu et al. (2012) explored how efficient this star formation is in the stellar mass accretion of BCGs, with a large sample of H\(\alpha\) line-emitting BCGs from the SDSS, and found that the star formation is not large enough to contribute to more than 1 per cent of the total stellar mass in the last 2 billion years.

The GAMA spectra are used to identify the activity in the BGG/BCGs sample and quantify the star formation rates. 236 BGG/BCGs (27 ± 1 per cent of the whole sample) have AGN, and 235 (27 ± 1 per cent of the whole sample) are forming stars. It is not possible to determine the activity level for 412 (46 per cent of the whole sample) galaxies as they do not have the necessary emission lines. Of these, 107 show H\(\alpha\) line emission (12 per cent of the whole sample). These galaxies are likely to be either AGN or star forming, however without the necessary lines it is not possible to distinguish between these possi-
2.5. AGN and Star formation activity

Figure 2.8: Histograms of cluster halo mass evolved to the present epoch for low (upper panel; $0.09 \leq z \leq 0.17$) and high redshift (lower panel; $0.17 < z \leq 0.27$) samples. **Left-hand panels:** $M_{\text{halo}}$ distribution (mass evolved to present epochs) for the whole sample per redshift bin. The differences in the median halo masses are illustrated by the dotted lines. **Right-hand panels:** Matched histograms after selecting the clusters, from the high-$z$ and low-$z$ samples, with similar halo masses. Each subsample contains 113 clusters, i.e. 113 BCGs. A halo mass like for like comparison is guaranteed between the two different redshift bins.

The remaining 305 galaxies (34 per cent of the whole sample) are passive. This section now focuses on the BGG/BCGs that have been confirmed to either have AGN, star formation or are passive (i.e., the uncertain systems are excluded). The distinction between BGGs and BCGs is based on the halo mass of their host systems. BGGs have stellar masses of $10^{10.6} < M_* < 10^{11.6} M_\odot$ while BCGs are generally more massive ($10^{11.2} < M_* < 10^{11.8} M_\odot$).

Figure 2.10 shows the fractions of BGG/BCGs that have star formation, AGN or are passive as a function of their stellar mass. Both BGGs and BCGs follow a trend of decreasing fraction of star-forming galaxies with increasing stellar mass as seen in other galaxy samples (e.g., Knappmann et al. 2003, Wijesinghe et al. 2011). In contrast, the fraction of AGN remains fairly constant ($\sim 0.25$) for the BGGs, and increases with stellar mass for the BCGs.

Here the star formation rates (SFRs) of those BGG/BCGs that show star formation (235
BGG/BCGs) is now examined. Their star formation rates extend from the GAMA detection limit of 0.1 \( M_\odot \)yr\(^{-1}\) up to the maximum reliable measure of 100 \( M_\odot \)yr\(^{-1}\). However, the median SFRs as a function of stellar mass are of the order of 1 \( M_\odot \)yr\(^{-1}\). The upper panel of Figure 2.11 shows the median SFR as a function of median \( M_\ast \). In this Figure it is clear that BGGs are the galaxies that are actively star-forming. The BCGs show little to no star formation. The bottom panel of Figure 2.11 shows the distribution of SFR in each of the \( M_\ast \) bins; each stellar mass bin contains 59 BGG/BCGs. Note the strong inverse relationship between median SFR and stellar mass. The least massive bin (median \( M_\ast = 10^{10.91} M_\odot \)) is dominated by the BGGs and presents the galaxies with the highest median SFR. The most massive bin (median \( M_\ast = 10^{11.51} M_\odot \)) predominently comprises BCGs with very low SFRs (\(< 1 M_\odot \)yr\(^{-1}\)).

Figures 2.12 and 2.13 are equivalent to Figure 2.10 and 2.11 but as a function of halo mass. Figure 2.12 shows that the fraction of AGN is constant with halo mass, as it is
with stellar mass. In contrast, the fraction of star-forming BGG/BCGs does not vary as strongly with halo mass, as it does with stellar mass, suggesting that star formation in BCGs is more likely to be dependent on stellar mass rather than environment, like the broader GAMA population (Wijesinghe et al., 2012). The fraction of passive galaxies increases with halo mass similarly to stellar mass. The upper panel shows the SFR as a function of halo mass. The SFR decreases as a function of increasing halo mass; this is examined further below. The bottom panel, shows the distribution of the SFR for each bin in the upper panel. The distribution of SFR does not change with halo mass as it does for stellar mass, further suggesting that in groups and clusters, stellar mass (rather than environment) seems to be driving the SFR relationships.

The specific SFR (sSFR) is a strong indicator of the star formation evolution of the galaxy, correlating current with previous SFR. Figure 2.14 shows the sSFR as a function of stellar mass for the BGG/BCGs that are star-forming in this sample. To analyse the effects of covariance between the sSFR and stellar mass, I first study the correlation between SFR and stellar mass. A Pearson coefficient of 0 reflects no correlation between the two quantities. A Pearson coefficient of 1 (-1 in the case of anticorrelation) would reflect a strong correlation between the two variables. I find that the Pearson coefficient between SFR and stellar mass is -0.48 with a probability of a null hypothesis (p-value) of 4.062e-13. This suggests a strong dependence of SFR on stellar mass. In the case of sSFR as a function of stellar mass, I find a Pearson coefficient of -0.70 with a p-value of 4.65e-31.

The anticorrelation between sSFR and stellar mass is slightly stronger than that between SFR and stellar mass. This could be due to the sSFR definition, which makes the sSFR inverse proportional to stellar mass. This causes an enhanced correlation between the two properties. However, the main driver of this relationship is the SFR. Therefore, the anticorrelation of sSFR as a function of stellar mass is real and suggests that at higher stellar masses the sSFR decreases.

A value of sSFR = 1 × 10^{-11} yr^{-1} implies that the galaxy would take 10 Hubble times (10^{11} years) to produce as much mass as it currently has. This means that galaxies with lower sSFRs are currently passive compared to their previous star formation. Higher sSFRs imply that galaxies are currently more active (e.g. McGee et al., 2011). Here 19 ± 1 per cent of the star-forming BGG/BCGs are active, and 81 ± 1 per cent are passive. The uncertainties are fractional errors. The relationship between sSFR and halo mass is not
shown as it is similar to, but weaker than the relationship between sSFR and stellar mass and is likely driven by the stellar mass–halo mass relationship.

To test the accuracy of the trends in AGN/SF observed, I removed the galaxies within 2σ line error (i.e. $2 \times 10^{-17}$ erg s$^{-1}$ cm$^2$ in the line flux measurements) of the AGN/SF division line in the BPT diagram. This will remove galaxies that could contain AGN and SF activity simultaneously and might be misidentified by measured uncertainties. The fraction of AGN and star-forming galaxies do not vary from the one previously observed. The SFR as function of stellar mass shows a Pearson coefficient of -0.55 and a p-value of 1.12e-13, consistent with the one observed for the whole sample (-0.48, p-value 4.06e-13). The sSFR as function of stellar mass shows a Pearson coefficient of -0.74 and a p-value of 1.19e-28, also consistent with the one observed for the whole sample (-0.70, p-value 4.65e-31).

In summary, BGGs are not completely inactive, however, most of the BCGs have been shown to be passive. The percentage of activity, either AGN or star formation, out of the large GAMA sample is 54 per cent, but this is a lower limit owing to the 12 per cent of galaxies which have Hα emission which cannot be distinguished between AGN and star formation. Nevertheless, the average star formation rates are low ($< 10 M_\odot$ yr$^{-1}$). This is consistent with the results of Liu et al. (2012) who found that the average star formation in 120 BCGs from SDSS ($0.1 < z < 0.4$) contributes to less than 1 per cent of their stellar mass over the last 2 billion years.

### 2.6 BGG/BCG position within its host halo

The position of the brightest galaxy in a group or cluster does not always correspond to the centre of the potential well (Beers et al. 1983; Zabludoff et al. 1993; Lazzati & Chincarini 1998; Lin & Mohr 2004; von der Linden et al. 2007; Pimbblet et al. 2006; Coziol et al. 2009; Skibba et al. 2010). In the GAMA sample I find that 13 ± 1 per cent of the BGG/BCGs do not lie at the centre of the dark matter halo potential well (hereafter non-central BGG/BCGs), i.e. 117 BGG/BCGs out of 883. The uncertainty is a fractional error. This is consistent with predictions made by some SAMs ($f \sim 0.15$, Croton 2006; Lo Faro et al. 2009) and slightly smaller than that measured by Skibba et al. (2010, $f \sim 0.25$) in a larger sample of $\sim 2200$ groups ($N \geq 4$).

The offset between the BCG and the central galaxy is the projected spatial distance
2.6. BGG/BCG position within its host halo

Figure 2.10: Fraction of ongoing star formation (solid lines), AGN activity (dotted line), and no activity (dashed line) in BGG/BCGs as a function of $M_\star$. The error bars represent fractional errors. The fraction of star-forming galaxies decreases with stellar mass, while the fraction of AGNs increases with stellar mass at the high mass end.

between these two galaxies within of the halo. The non-central BGG/BCGs can be found anywhere between 80 kpc and $\sim 1$Mpc away from the halo centre. Note that the two subsamples, central and non-central BGG/BCGs will be contaminated by objects in the other subsample, since the iterative centre of light method of determining the halo centre is correct only 90 per cent of the time (see Section 2.2.1). I have used the GAMA mock catalogues to test the level of contamination. While the mock catalogues overestimate the fraction of BCGs offset from the true halo centre compared to the observations, they do provide an estimate of the fraction of contamination of the non-central BCG sample, which is $\sim 1/3$. The impact of the cross-contamination is to dilute the differences that are observed. The real differences between central and non-central BCGs are therefore likely to be stronger than that reported here.

The fraction of non-central BGG/BCGs varies with $M_{\text{halo}}$ (Figure 2.15). In agreement with previous studies, more massive halos are more likely to host a non-central BCG (Cozzi et al., 2009; Skibba et al., 2010; Martel et al., 2014). Since no significant differences between groups and clusters are found, in this Section BGGs and BCGs are studied as one continuous population.
Figure 2.11: SFR of BGG/BCGs as a function of stellar mass. **Upper panel:** Median star formation rate of the galaxies that are star forming (235 out of 883 BGG/BCGs) as a function of stellar mass. The BGGs are shown as circles, and the BCGs as triangles. The black dots represent the median per bin. The error bars represent the standard deviation. The SFR decreases with stellar mass. **Lower panel:** The distribution of the SFR per median $M_*$ bin, each histogram corresponds to a point in the upper panel and contains 59 BGG/BCGs. The median SFR is shown as a dotted line. Note how the galaxies gradually quench with increasing stellar mass.
2.6. BGG/BCG position within its host halo

Figure 2.12: Fraction of ongoing star formation (solid lines), AGN activity (dotted line), and no activity (dashed line) in BGG/BCGs as a function of $M_{\text{halo}}$. The error bars represent fractional errors. The fraction of star-forming galaxies decreases with halo mass, while the fraction of AGNs is fairly constant.

2.6.1 How different are central from non-central BGG/BCGs?

In order to avoid biases in sample selection, the velocity dispersion distributions of the non-central and central BGG/BCGs halos need to be similar enough for these two subsamples to be compared accurately. Therefore, the properties of the halos are checked using the “modality” parameter described in Section 2.2.1. The modality gives information about the Gaussianity of the velocity dispersion distribution in the halo. Halos with modality $\sim 0.33$ have Gaussian velocity distributions and can be considered to be relaxed. The left-hand panel of Figure 2.16 compares the modality distributions between the central (shaded) and non-central BGG/BCGs (open) with a Kolmogorov-Smirnov test (hereafter K-S test). There is a probability of 52 per cent that the two sub-samples are similar in their Gaussianity. This means that the central and non-central BGG/BCGs are drawn from similar parent groups. Now it is safe to proceed to analyse the properties of the galaxies and their host halos in these different subsamples.

The amplitude of the luminosity gap between the BGG/BCG and the second brightest galaxy in the halo (here referred to as the dominance, see Section 2.2.1), is expected to be a function of both the formation epoch and the recent infall history of the halo. A
low dominance ($\Delta m_{1,2} < 1$) indicates a recent halo merger, and larger gaps ($\Delta m_{1,2} > 1$), common in fossil groups, is perhaps indicative of a cluster or group that has not undergone...
2.6. BGG/BCG position within its host halo

Figure 2.14: Median specific star formation rate of the galaxies that are star forming (235 out of 883 BGG/BCGs) as a function of stellar mass ($M_*$). The BGGs are shown as circles, and the BCGs as triangles. The black points indicate the medians of 59 BGG/BCGs. The error bars represent the standard deviation. The dotted line ($sSFR = -11$ dex) represents the division between active and passive galaxies, defined by McGee et al. (2011). A fraction of $0.19 \pm 0.01$ of the galaxies are above the threshold.

...a recent merger. BCGs are expected to be located in clusters with large luminosity gaps (e.g. Tremaine & Richstone 1977a; Loh & Strauss 2006; Smith et al. 2010). This sample has a wide range of dominance ($0 < \Delta m_{1,2} < 3.1$; Figure 2.16), having a long tail towards the higher values. A fraction of $20 \pm 11$ per cent have $\Delta m_{1,2} > 1$ and $3 \pm 4$ per cent have $\Delta m_{1,2} > 2$. Smith et al. (2010) analysed the dominance of a sample of 59 massive galaxy clusters ($10^{14}$ to $10^{15} M_\odot$) and found a fraction of $0.37 \pm 0.08$ of their sample had $\Delta m_{1,2} > 1$ and $0.07 \pm 0.05 \Delta m_{1,2} > 2$. These results are consistent with their findings despite the lower average halo mass of the sample.

If halos hosting central and non-central BGG/BCGs are going through different processes of evolution, this should be reflected in the halo dominance. The central panel of Figure 2.16 shows the dominance distributions for central BGG/BCGs (shaded), and non-central BGG/BCGs (open). From a K-S test results the central and non-central BGG/BCGs have significantly different distributions (probability = $2.42e^{-21}$ of being drawn from the same parent population). Non-central BGG/BCGs have lower dominance which suggests that they reside in halos which are more likely to have undergone a recent halo merger. This
Chapter 2. BGG/BCG stellar mass growth since $z = 0$

Figure 2.15: Fraction of halos where the BGG/BCG is not centrally located, shown as a function of halo mass. The error bars represent the fractional errors. The fraction of non-centrally located BGG/BCGs increases with increasing halo mass.

is consistent with a naive merger model in which the new system contains two massive bright galaxies, that with time will merge into one.

To further test this hypothesis, I analyse the relative halo overdensity, which refers to the number of objects surrounding the halo within a given comoving cylinder (see Section 2.2.1), as a proxy for the isolation of the halo. A K-S test performed on these data gives a probability of $= 1.23 \times 10^{-9}$ for the two subsamples to be similar, which implies that the halos hosting central and non-central BGG/BCGs are in different overdensities. The halos with non-central BGG/BCGs are, on average, part of larger systems (Figure 2.16 right-hand panel). This would increase the chances of groups or galaxies falling into the group or cluster.

Figure 2.17 shows the $M_\star - M_{\text{halo}}$ relationship for central (red crosses) and non-central (blue circles) BGG/BCGs. Both subsamples follow the same power law within the error bars ($\sim 0.32 \pm 0.2$), i.e. both subsamples grow at the same rate as a function of $M_{\text{halo}}$. However, they are offset in stellar mass. The central BGG/BCGs are generally more massive than the non-central BGG/BCGs ($\sim 0.3$ dex, i.e. on average two times more massive) for a given halo mass. This is also consistent with the naive merger model where the new
2.6. BGG/BCG position within its host halo

Figure 2.16 Normalised distributions of modality (left-hand panel), dominance ($\Delta m_{1,2}$, central panel), and relative overdensity (right-hand panel) for central and non-central BGG/BCGs (shaded and open bars respectively). The non-central BGG/BCGs are in halos with lower dominance and higher relative overdensities. Low dominance and high relative overdensities both suggest the possibility of recent halo-halo mergers.

Halo contains the combined mass of both halos, but the merger of the two dominant galaxies is yet to take place.

Stott et al. (2012) analysed the BCG luminosity as a function of the BCG offset from the centre of the cluster, finding little correlation between these two properties (power-law index of $0.09 \pm 0.05$). However, in this analysis a different approach has been taken from Stott et al. (2012). The halo mass has been fixed to compare the central and non-central BGG/BCGs without taking into account the degree of spatial offset. This suggests that the difference in properties is a sharp function of whether the BCG is at the centre of light or not.

I also analyse whether the AGN and SF activity of the central BGG/BCGs are different to that of the non-central BCGs. The feedback prescriptions implemented in SAMs
Chapter 2. BGG/BCG stellar mass growth since $z = 0$:

Figure 2.17: BGG/BCG stellar mass - host halo mass relationship for central BGG/BCGs (red crosses) and non-central BGG/BCGs (blue circles). The thick line represents the best fit for central BGG/BCGs. The thin line represents the best fit for non-central BGG/BCGs. The measurement uncertainties are shown at the bottom of the panel in halo mass bins. The central and non-central BGG/BCGs stellar mass - host halo mass relationship are offset in stellar mass by 0.3 dex (a factor of 2) for a given halo mass.

assume that AGN are hosted in central galaxies only. Therefore, more AGN activity is expected in central BGG/BCGs. However, the fraction of AGN activity and star-forming galaxies does not differ between the central and non-central BGG/BCGs, implying that neither form of activity is environment-dependent for the galaxies in the sample. This is illustrated in Figure 2.18, where the fraction of AGN and star-forming BGG/BCGs are shown as a function of $M_{\text{halo}}$ and $M_*$, respectively. Both subsamples (central and non-central BGG/BCGs) follow similar trends: the fraction of AGN remains constant while that of the SF decreases with stellar mass. This suggests that neither form of activity depends on the position of the BCG within the halo.

2.7 Discussion

2.7.1 Comparison with galaxy formation and evolution models

This Chapter has presented the observations of 883 brightest group and cluster galaxies taken from the GAMA survey (Driver et al., 2011). The sample contains groups and clus-
Figure 2.18: AGN and SF activity in central and non-central BGG/BCGs. Fraction of AGNs (upper panels) and star-forming galaxies (lower panels) for central and non-central BGG/BCGs (red solid line and blue dashed lines respectively) as a function of $M_{\text{halo}}$ (left-hand panels) and $M_*$ (right-hand panels). The points represent bins of equal galaxy numbers in a specific mass range. The uncertainties are fractional errors. These fractions do not show a dependance on BCG position in the halo.

M ters with multiplicities $\geq 5$ covering a halo mass range of $10^{12} < M_{\text{halo}} < 10^{15} M_\odot$. The index found in the power law of the $M_* - M_{\text{halo}}$ relationship is $b = 0.32 \pm 0.09$. This is in agreement with Lin & Mohr (2004) who found $L_K \propto M_{200}^{0.26}$, Brough et al. (2008) who found $L_K \propto M_{200}^{0.34}$, and Hansen et al. (2009) who found $L_\gamma \propto M_{200}^{0.3}$. However, Stott et al. (2012) found a much steeper $M_* - M_{\text{halo}}$ relationship ($b = 0.78 \pm 0.07$) from an X-ray selected sample of BCGs at $z < 0.3$. This is similar to the power-law found by Lidman et al. (2012), i.e. $0.63 \pm 0.07$ over a broader redshift range, $0.05 \leq z \leq 1.6$. The discrepancies between the power-law values in each analysis could be redshift dependent, but could also be the result of the different methods used in the estimation of galaxy luminosity/mass and halo mass as well as the variety of fitting methods employed.

Moster et al. (2013) have used an abundance-matching model, statistically constrained by observations, to predict the $M_* - M_{\text{halo}}$ relationship since $z \sim 4$. They predict the slope of the relationship to be redshift dependent. The relationship observed here is consis-
tent with their prediction in the high stellar mass range (10^{10.5} to 10^{12} \, M_\odot for z < 0.3). However, the degree of evolution that they predict with redshift depends on observational uncertainties in the stellar mass values, which highlights the effect of the systematics in these measurements.

Analysing the growth in the stellar mass of the BGG/BCGs, no significant growth between z = 0.27 and the present day is found, for either groups and clusters. By comparing the median stellar mass corresponding to the median redshifts of the subsamples (\bar{z} = 0.136 and \bar{z} = 0.214), a stellar mass ratio of 0.92 ± 0.07 for the groups, and 0.93 ± 0.09 for the clusters is found. For the median BGG stellar mass and group mass range (median M_\ast = 10^{11} \, M_\odot, median M_{\text{halo}} = 10^{13} \, M_\odot) the results presented here agree remarkably well with those predicted by Moster et al. (2013). The cluster results are consistent with Lin et al. (2013) who analysed the growth of BCGs in clusters from the Spitzer IRAC Shallow Cluster Survey (ISCS), with halo masses between (2.5 - 4.5) \times 10^{14} \, M_\odot. They found slow growth at redshifts z < 0.5 (less than 10 per cent), with more rapid growth (a factor of 2.3) at high redshifts 0.5 < z < 1.5. These observational results are in agreement with the SAMs (De Lucia & Blaizot, 2007; Tonini et al., 2012) at higher redshifts, finding some differences at lower redshifts.

SAMs predict that a BCG acquires \sim 30 per cent of its stellar mass since z = 0.3, and more than 10 per cent between the median values of the two redshift bins (\bar{z} = 0.136 and \bar{z} = 0.214). The cluster results overall show no growth in this redshift range. Nevertheless, a 10 per cent growth cannot be completely ruled out, given that the 1\sigma error would mean \sim 9 per cent growth for the BCGs and \sim 7 per cent growth for BGGs.

The comparison between this result and those of other authors is illustrated in Figure 2.19. This Figure shows the BGG (lower panel) and BCG (upper panel) stellar mass ratio evolution over cosmic time. The upper panel compares the cluster in this work (red circles) with the cluster observations of Lidman et al. (2012) green triangles), and Lin et al. (2013) blue dots), and the SAMs of De Lucia & Blaizot (2007, black line) and Tonini et al. (2012, yellow dots) as well as the dark matter simulations of Laporte et al. (2013, grey diamonds). In order to compare observations with models, the highest redshift point of each observational data set has been normalised to the De Lucia & Blaizot (2007) model. This is justified by the conclusions of Lin et al. (2013) whose BCGs were consistent with the models at z > 0.5 but become increasingly inconsistent at lower redshifts. The most
appropriate way to normalise each observational sample would be to normalise each ob-
servational sample at each redshift. However, as the analysis presented in these papers are
different making a direct comparison between each observation and the model is the most
appropriate comparison. The BCGs are observed to acquire their stellar mass rapidly
from $z = 1.5$ to $z = 0.3$, in agreement with the model predictions. The lowest redshift
point in all three samples lies below the model curve. This effect of fast growth at high
redshifts is also seen in massive field galaxies (e.g. Conselice et al. 2007).

The lower panel of Figure 2.19 shows the comparison of the groups in the GAMA obser-
vations (red circles) with the predictions from the abundance-matching model of Moster
et al. (2013) dashed line). The highest redshift point of the observations is normalised to
the model. This model is consistent with the low-redshift observations. Unfortunately,
groups data are not available at higher redshifts, so this does not allow us to draw any
conclusions on BGG stellar mass growth.

BCG mass growth is observed to be much slower at low redshift than models predict.
The discrepancy with the models suggest that there is some factor in their growth that is
not being accounting for. BCGs have grown mainly through mergers (e.g. Lidman et al.
2013) rather than star formation. While models do take into account the timescales for
galaxies to merge, they do not always take into account the efficiency of that merging.
The efficiency may also evolve with time such that a higher fraction of merging galaxies
break-up to become part of the intracluster light at low redshifts (e.g. Conroy et al. 2007;
Puchwein et al. 2010). This would result in less mass being added to BCGs in mergers
at low redshifts. However, more observations are required to confirm this hypothesis.

2.7.2 AGN/SF activity in BGGs and BCGs

At least 27 per cent of the galaxies in this GAMA sample are found to be actively star-
forming and another 27 per cent are found to be AGN (classified optically with the BPT
diagram of Kewley et al. 2001). The fraction of BGGs that host AGN remains fairly
constant (0.25) with stellar mass. This fraction increases slightly at the high stellar mass
end probed by BCGs, but not significantly. This is consistent with Stott et al. (2012) who
studied the same stellar mass range in X-ray-selected BCGs and found that the fraction
hosting radio-loud AGN is constant with stellar mass. Also the AGN fraction is con-
stant with halo mass, showing no environmental dependence above the lowest halo mass
of $M_{\text{halo}} \sim 10^{13} M_\odot$. This contrasts with Stott et al. (2012) who found an increase of
Chapter 2. BGG/BCG stellar mass growth since \( z = 0.3 \)

Figure 2.19: Stellar mass ratio evolution with cosmic time. Comparison between observations and hierarchical structure formation models. **Upper panel:** Comparing the observations presented here (red circles) with the semi-analytic models of De Lucia & Blaizot (2007, black line) and Tonini et al. (2012, yellow dots) and the dark matter model of Laporte et al. (2013, grey diamonds). This panel also shows observations from Lidman et al. (2012, green triangles) and Lin et al. (2013, blue dots). Each of the observations are normalised to De Lucia & Blaizot (2007)’s model by fixing the highest redshift point to the model. The errors were estimated through bootstrapping. The observations follow similar stellar mass growth as the one predicted by the SAMs at high redshifts \( (z > 0.3) \), however, this is not the case at lower redshifts. There is a tendency for the low redshift point in each sample to lie below the model predictions. The observations suggest little to no stellar mass growth at \( z < 0.3 \) in contrast with the continuing growth predicted by the models. **Lower panel:** Comparing the BGG observations (red circles) to the abundance matching model of Moster et al. (2013, dashed line) for the group mass range (median \( M_\ast = 10^{11} M_\odot \), median \( M_{\text{halo}} = 10^{15} M_\odot \)). The errors were estimated through bootstrapping. The results agree with the model predictions within error bars.
2.7. Discussion

The fraction of BCGs hosting radio-loud AGN with increasing halo mass (from $f \sim 0.1$ at $M_{500} \sim 10^{13.9} \, M_\odot$ to $f \sim 0.38$ at $M_{500} \sim 10^{14.7} \, M_\odot$).

The fraction of star-forming galaxies decreases (from 0.4 to 0.16) with increasing stellar mass for both groups and clusters, while it is fairly constant with halo mass. From the analyses of the SFR in the BGG/BCGs that are star-forming, the median SFR is higher ($\sim 8 \, M_\odot \, yr^{-1}$) in the less massive galaxies ($10^{10.6} \, M_\odot < M_* < 10^{11} \, M_\odot$), which are mostly BGGs, than in the more massive galaxies which are mostly BCGs ($\sim 1 \, M_\odot \, yr^{-1}$). This is consistent with the studies of other galaxy populations (e.g. [Wijesinghe et al., 2012] and the predictions made by the abundance matching model of [Yang et al., 2013]). They found from a volume-limited sample of BCGs with $M_* > 10^{11} \, h^{-1} \, M_\odot$, that these galaxies are predominantly quenched. GAMA BCGs with masses more than $M_* > 10^{11.3} \, M_\odot$ are mostly quenched (Figure 2.11). These trends are driven by stellar mass rather than by the host group/cluster environment. Overall $\sim 19$ per cent of the star-forming BGG/BCGs can be identified as active galaxies ($sSFR > 1 \times 10^{-11} \, yr^{-1}$; [McGee et al., 2011]). Leaving $\sim 81$ per cent as passive galaxies. The active galaxies are mainly BGGs.

BGGs are not completely quenched, while BCGs present significantly less star formation but higher fractions of AGN activity. Nevertheless the star formation rates for both BGGs and BCGs are not high enough to contribute significant amounts of stellar mass in these giant galaxies. In general most of the BGGs and BCGs have SFR $< 3 \, M_\odot \, yr^{-1}$. The results of this analysis agree with those of [Liu et al., 2012]. However, this fact cannot be overlooked in theoretical work. [Tonini et al., 2012] showed that by including star formation in SAMs the predicted photometric colours, they reproduce the observations. More specifically, luminosities in the K-band in their model are in better agreement with the observations of [Brough et al., 2008], [Stott et al., 2008], [Collins et al., 2009], and [Lidman et al., 2012] than previous models.

2.7.3 Central versus non-central BGG/BCGs

I find that 13 per cent of the BGG/BCGs in the GAMA sample are not centred in their host halo. This fraction is consistent with that predicted in SAMs ($0.1 < f < 0.2$; [Croton, 2006], [Lo Faro et al., 2009]) as well as the N-body simulations of [Martel et al., 2014]. In contrast, [Skibba et al., 2010] in a sample selected from the SDSS group catalogue found a larger fraction ($0.25$ for $M_{\text{halo}} \sim 10^{12} - 10^{13} \, M_\odot$ to $0.4$ for $M_{\text{halo}} = 5 \times 10^{13} \, M_\odot$). Despite the difference between the GAMA sample and that of [Skibba et al., 2010], the overall
conclusions are in agreement. The fraction of non-central BCGs increases with increasing $M_{\text{halo}}$ (Figure 2.15).

After analysing the properties of the halos of the BGG/BCGs in this sample using the dominance ($\Delta m_{1,2}$) and relative overdensity parameters (Figure 2.16), the non-central BGG/BCGs halos show significantly smaller $\Delta m_{1,2}$ values, and higher relative overdensities. In contrast, central BGG/BCGs halos are shown to have a broader range of values ($0 < \Delta m_{1,2} < 3.4$). The dominance and overdensity results both suggest that the non-central BGG/BCGs are likely to be a result of recent halo-halo mergers. This conclusion is further strengthened by the difference in stellar mass between the central and non-central BGG/BCGs. The non-central BGG/BCGs have most likely fallen into their current system as the central galaxy of a lower mass system. Dynamical friction will act upon this BGG/BCG, causing it to fall to the centre of its new system. The fact that the fraction of non-central BGG/BCGs increases with increasing halo mass suggests that the timescale for the BCG to merge with the central galaxy of the other halo is longer than those assumed by models (Martel et al., 2014).

The dominance and overdensity results observed are confirmed by the simulations of Martel et al. (2014) who follows the merger trees of 18 massive cluster ($M_{\text{cl}} > 10^{14} M_{\odot}$). Major cluster-cluster mergers can drastically change the central position of the BCG. This galaxy remains offset (slowly moving into the centre) while the cluster is “unrelaxed” as a remnant of the merging event. The majority of the clusters (15 out of 18) have reached a relaxed state at $z = 0$ showing why the observed fraction of central BCGs is higher.

2.8 Summary and conclusions

The galaxies presented in this Chapter are a large (883 galaxies) and homogeneous sample of low redshift ($0.09 < z < 0.27$) brightest group and cluster galaxies from the Galaxy And Mass Assembly (GAMA) survey. The results draw the following conclusions:

(a) By comparing the BGG/BCG stellar mass in like-with-like halos no significant growth over this period of cosmic time is found. After comparing the results with previous analyses it could be concluded that BCGs acquire their stellar mass rapidly at early epochs ($z > 0.3$). Below redshift $z \sim 0.3$ the stellar masses increase more slowly. This is possibly because the timescales or efficiencies for merging evolve. While observations are more consistent with the models (SAMs and abundance-matching models) at higher redshift,
there are still small discrepancies at low redshifts. I stress the importance of taking into account the stellar mass - halo mass relationship for such a comparisons.

(b) The BGG/BCGs are not completely dormant; at least 27 per cent of the sample host AGN and another 27 per cent are star forming. Their star formation rate decreases with stellar mass, from $10 \, M_\odot \, \text{yr}^{-1}$ at $M_* \sim 10^{10.8} \, M_\odot$ to less than $1 \, M_\odot \, \text{yr}^{-1}$ at $M_* \sim 10^{11.6} \, M_\odot$. Therefore, BGGs are actively star-forming while BCGs are mostly quenched with higher fractions of AGN activity. At stellar masses $10^{11} \, M_\odot < M_* < 10^{11.4} \, M_\odot$ there is a bimodal population of star-forming and quenched systems. Despite the presence of star-formation in BCGs the SFRs are not high enough for star formation to contribute significantly to the stellar mass growth of these galaxies.

(c) I examine the position of the BGG/BCGs with respect to their dark matter halo and find that around $\sim 13$ per cent of the BGG/BCGs are not centrally located. The halo properties, dominance and relative overdensity, in non-central BGG/BCGs halos suggest that these halos have undergone recent mergers. This is further proven by the stellar mass difference between central and non-central BGG/BCGs. This suggests that non-central BGG/BCGs were the central galaxies in smaller systems that fell into the observed systems not long ago. The fraction of AGNs and star-forming galaxies is similar for central and non-central BGG/BCGs.
The accretion histories of brightest cluster galaxies from their stellar population gradients

The central galaxies of massive clusters (brightest cluster galaxies, BCGs) are expected to be the end product of an active accretion history. This Chapter presents the stellar populations of nine local ($z < 0.1$) BCGs observed with an IFS unit. This analysis examines the connection between the central stellar population parameters and stellar population gradients with the galaxy’s recent mergers. The results are compared to the stellar populations of massive early-type galaxies, exploring whether BCGs are distinct galaxies or not.

—Oliva-Altamirano et al. 2015, 449, 3347

3.1 Introduction

In the hierarchical scenario of structure formation (Toomre 1977; White & Rees 1978) Brightest Cluster Galaxies (BCGs) are predicted to have a more active merger history than lower mass galaxies (White & Rees 1978; Khochfar & Burkert 2003; De Lucia & Blaizot 2007; Oser et al. 2010; Naab et al. 2014). These galaxies are often considered as the extreme end-point of massive galaxy evolution. However, despite being among the most luminous galaxies, and generally easy to detect, observations and theory have not reached a common point yet, and their evolution is still not fully understood.

Observations suggest that the mass growth of BCGs evolves with time. BCGs accrete their mass at a fast rate until $z \sim 0.5$, thereafter their mass growth slows down (Lidman et al. 2013; Lin et al. 2013; Oliva-Altamirano et al. 2014; Inagaki et al. 2014; Shankar et al. 2014 2015). Studies looking at BCG companions have concluded that their stellar mass grows through major mergers ($\geq 1 : 3$ mass ratios) by a factor of $1.8 \pm 0.43$ at
$0.8 < z < 1.5$ (Burke & Collins, 2013), and mostly by minor mergers ($\leq 1 : 4$ mass ratios) by a factor of 1.1 at $z < 0.3$ (Edwards & Patton, 2012). Major mergers are rare at low redshifts, yet still possible (e.g. Brough et al., 2011; Jimmy et al., 2013).

The recent accretion history of galaxies can be read through their stellar population gradients. In the canonical scenario, a galaxy’s initial metallicity gradient is set by an initial starburst at $z \geq 3$ and the metallicity decreases in the outskirts, as metallicity follows the changes in the gravitational potential (Scott et al., 2009; McDermid et al., 2012). This gradient can be disrupted by violent merging events (major mergers), or reinforced by minor mergers (Kobayashi, 2004; Spolaor et al., 2009; Cooper et al., 2010; Pipino et al., 2010). Hirschmann et al. (2015) analysed the stellar populations of 10 massive halos ($10^{12} < M_{\text{halo}} < 10^{13} \, M_{\odot}$) from the high-resolution cosmological simulation of Hirschmann et al. (2013). They found that major mergers do flatten the metallicity gradients. If, as predicted, BCGs have an active merger history, including several major mergers, they would be expected to have shallower metallicity gradients than lower mass galaxies. However, long-slit observations to date suggest that they have a wide range of gradients (Brough et al., 2007; Loubser & Sánchez-Blázquez, 2012).

Integral Field Spectroscopy (IFS) is a valuable tool to explore the spatially-resolved kinematics and stellar populations of galaxies. The SAURON (de Zeeuw et al., 2002) and ATLAS$^{3D}$ (Cappellari et al., 2011) surveys have used IFS to explore a significant sample of early-type galaxies in the local Universe. Kuntschner et al. (2010) and McDermid et al. (2015) presented the stellar population analysis of the SAURON and ATLAS$^{3D}$ samples, respectively, finding that 40 per cent of the galaxies typically show contributions from young stellar populations connected to low mass, fast rotator systems. In contrast, they find that slow rotators are generally consistent with old ($\geq 10$ Gyr) stellar populations. The most massive systems (stellar mass $\geq 10^{10.5} M_{\odot}$) have the flattest metallicity gradients. However, the ATLAS$^{3D}$ sample only contains 21 galaxies with dynamical masses greater than $10^{11.3} M_{\odot}$, and only one contains the BCGs from the Virgo cluster (3 massive galaxies).

Jimmy et al. (2013) analysed the kinematics and photometry of a sample of 10 BCGs observed with the VIMOS IFS, of which 4 have close massive companions. If BCGs were the product of many mergers they would be expected to be slow-rotating galaxies. Jimmy et al. (2013) found that 30 per cent of the BCGs in their sample are fast rotators. The
3.2 Observations

Simulations of Naab et al. (2014), predict that angular momentum mostly depends on the gas content of the galaxies involved in the interaction, suggesting that the slow or fast rotation could be a temporary state. Jimmy et al. (2013), also find through photometric analysis \(G - M_20\); Lotz et al. (2008) that 40 per cent of the galaxies in their sample have undergone a minor merger within the last 0.2 Gyr.

This Chapter presents the spatially—resolved stellar populations of the BCG sample presented in Jimmy et al. (2013). To-date this is the first IFS analysis dedicated to the stellar populations of BCGs. The aim is to investigate whether BCG accretion histories are different from those of the general massive early-type galaxy population by comparing the measurements presented here to those from SAURON and ATLAS3D.

3.2 Observations

This Section summarises the observations made and the data reduction process. These are described in full in Jimmy et al. (2013).

3.2.1 Spectroscopic Measurements

The BCG sample is selected from von der Linden et al. (2007). The galaxies are part of the C4 cluster catalogue (Miller 2005) of the third data release of the Sloan Digital Sky Survey (SDSS; York et al., 2000). These observations consist of 10 BCGs, 4 of which have massive companions within \(\sim 10''\) (corresponding to \(\sim 18\) kpc at \(z < 0.1\)). The nomenclature adopted is that of Jimmy et al. (2013), i.e. each cluster is presented as the last 4 digits in the SDSS flag, rather than SDSS-C4-DR3 number. The galaxies were observed with the Very Large Telescope using the IFS mode of the VIMOS spectrograph (Le Fèvre et al. 2003), with the high-resolution blue grism, which has a spectral resolution of \(R \sim 1400\) (0.57 Å/pixel). The observations were made in two sets, April to August of 2008 and April to July of 2011 (Prog. ID 381.B-0728 and Prog. ID 087.B-0366, respectively). The galaxies used in this study have a spatial sampling of 0.67''/pixel with a field-of-view (FOV) of 27'' \(\times 27''\). The average seeing of the observations is 0.9''. The rest wavelength range is \(\sim 3900\) to 5600 Å.

3.2.2 IFS Data Reduction

The IFS data reduction consists of two different stages: (a) The VIMOS Pipeline (Izzo et al. 2004) which generates the calibrations files (fibre identification, master bias, etc.),
and does a first order flux calibration. This flux calibration corrects the spectrum shape, using the standard stars observed on the same night as the galaxies. The VIMOS FOV is formed by four quadrants. The VIMOS pipeline reduces each quadrant separately. The result is the science spectrum for each spaxel (spatial pixel) in each quadrant. (b) Our own IDL routines are used to mask the bad fibres, subtract the sky for each quadrant and then combine the quadrants into a three dimensional data cube. The multiple exposures for each observation are combined using a 5σ clipped median. This code is publicly available. Finally, the flux calibration of the spectrum is done using the photometric standard stars.

3.3 Previous measurements

Jimmy et al. (2013) measured the stellar kinematics and photometry of the galaxies in this sample, following is the summary of their method and results.

3.3.1 Stellar Kinematics

First a signal-to-noise ratio (SNR) cut of 5 across all the spaxels was applied. The spaxels were then re-binned to a minimum SNR of 10, using the Voronoi spatial binning code of Cappellari & Copin (2003). The velocity and line-of-sight velocity dispersion were computed using the penalised fitting scheme of Emsellem et al. (pPXF; 2007), and the MILES (Medium-resolution Isaac Newton Telescope Library of Empirical Spectra; Sánchez-Blázquez et al., 2006a) library stellar templates. pPXF fits the stellar library templates to the absorption line features of the BCG spectra, giving the recession velocities and the broadening of the spectral lines.

The angular momentum was characterised by the $\lambda_R$ parameter defined by Emsellem et al. (2007). It is calculated as follows:

$$\lambda_R \sim \frac{\langle R|V| \rangle}{\langle R\sqrt{V^2 + \sigma^2} \rangle},$$

(3.1)

where $R$ represents the radius of the galaxy, $V$ is the stellar velocity and $\sigma$ the velocity dispersion. The numerator and denominator are luminosity weighted. A higher $\lambda_R$ represents a higher angular momentum. The ellipticity ($\epsilon$) at the effective radius of each galaxy was measured using the publicly available IDL routine find.galaxy.pro developed by Michele Cappellari. Following Emsellem et al. (2011), the values of $\lambda_R$ and $\epsilon$ can be found online.

1http://galaxies.physics.tamu.edu/index.php/Jimmy#Code
2http://www-astro.physics.ox.ac.uk/~mxc/idl/
used to distinguish fast and slow rotators (FR and SR respectively) by using the threshold:

\[ \lambda_R \geq (0.31 \pm 0.01) \times \sqrt{e}, \]  \hspace{1cm} (3.2)

where FRs lie above this threshold and SRs lie below.

The dynamical mass was measured using the standard equation given in Cappellari et al. (2006).

\[ M_{\text{dyn}} = \frac{5R_e \sigma_e^2}{G}, \]  \hspace{1cm} (3.3)

where \( \sigma_e \) is the aperture corrected velocity dispersion of the integrated spectrum within the effective radius; \( G \) is the gravitational constant. Table 4.3 summarises the relevant kinematic results. 7 of the BCGs are SR and 2 are FR. For \( \sigma_e, e \) and \( R_e \) the reader should refer to Table 2 of Jimmy et al. (2013).

**3.3.2 Photometric Analysis**

Jimmy et al. (2013) analysed the photometry of this sample using images from SDSS Data Release 3. They measured the effective radius by fitting a 2D de Vaucouleurs profile. They also analysed the presence of recent mergers using the Gini, and \( M_{20} \) coefficients (Lotz et al., 2008). This method studies the distribution of light looking for irregularities that could indicate morphological signatures of mergers. A galaxy is a merger candidate if it crosses the threshold:

\[ G \geq -0.14M_{20} + 0.33 \]  \hspace{1cm} (3.4)

Where \( M_{20} \) is the 2nd order moment of the brightest 20 per cent of pixels, and \( G \) is the Gini coefficient. In the case of gas-poor galaxies like those in this sample, a galaxy will be above the threshold if it is currently merging or has merged in the last 0.2 Gyr (Lotz et al., 2011). 4 of the BCGs in the sample are merging. The relevant kinematic and photometric results of Jimmy et al. (2013) are presented in Table 3.1.

**3.3.3 Stellar populations from the SAURON and ATLAS\textsuperscript{3D} samples**

Throughout this Chapter these observations are compared to those of early-type galaxies of similar mass observed by ATLAS\textsuperscript{3D} (which includes the SAURON galaxy sample). The ATLAS\textsuperscript{3D} sample is composed of 260 field and cluster early-type galaxies and one BCG, M87. The spatially-resolved stellar populations (central values and gradients) of the SAURON sample were presented in Kuntschner et al. (2010). The central stellar popul-
Table 3.1: Kinematic properties of BCGs and their companions from Jimmy et al. (2013). Seven of the BCGs are slow rotating (SR) and two are fast rotating (FR). Four of the BCGs show photometric signs of merging.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>z</th>
<th>log $M_{\text{dyn}}$ $M_\odot$</th>
<th>$R_e (''')$</th>
<th>Merging?</th>
<th>FR/SR</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCGs</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
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<td>6.98</td>
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<td>SR</td>
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<tr>
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<td>n</td>
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<tr>
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<td>n</td>
<td>SR</td>
</tr>
<tr>
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<td>5.07</td>
<td>y</td>
<td>SR</td>
</tr>
<tr>
<td>2001</td>
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<td>11.38</td>
<td>5.84</td>
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</tr>
<tr>
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</tr>
<tr>
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<td>y</td>
<td>SR</td>
</tr>
<tr>
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<td>FR</td>
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<tr>
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</tr>
<tr>
<td>1027B</td>
<td>0.090</td>
<td>11.17</td>
<td>4.39</td>
<td>y</td>
<td>FR</td>
</tr>
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<td>FR</td>
</tr>
<tr>
<td>1048C</td>
<td>0.074</td>
<td>10.54</td>
<td>1.24</td>
<td>y</td>
<td>FR</td>
</tr>
</tbody>
</table>

Kuntschner et al. (2010) and McDermid et al. (2015) use the stellar models of Schiavon (2007) in the Lick/IDS system (Worthey & Ottaviani, 1997) to measure the stellar population parameters of age, total metallicity [Z/H] and abundance of alpha elements [\(\alpha/Fe\)]. For the spectral fitting, the models used only have solar abundances, i.e. [\(\alpha/Fe\)] = 0. In this case [Fe/H] is effectively a measure of the total metallicity\(^3\). Therefore, the ATLAS\(^3D\) total metallicities are directly compared to the measured metallicities in this Chapter. The central stellar populations in the ATLAS\(^3D\) sample correspond to an aperture of 0.125 $R_e$.

Throughout the analysis the median, and standard deviation for the two samples in the same mass range ($M_{\text{dyn}} > 10^{11.3} M_\odot$) are compared. In order to compare these BCGs with a non-BCG early-type galaxy sample, BCG M87 is not included. This gives a comparison sample of 20 massive early-type galaxies from the ATLAS\(^3D\) sample. M87 is highlighted

\(^3\)[Fe/H] = [Z/H] - 0.75 * [\(\alpha/Fe\)] (Conroy & van Dokkum, 2012)
3.4 Stellar Population Analysis

The study of stellar populations requires high SNR spectra. In order to secure a high enough SNR I developed a new PYTHON routine to stack the spaxels within annuli for each galaxy in this analysis. The annuli are identified following the total flux in the wavelength-integrated galaxy image. This indirectly maps the galaxy morphology, i.e. the shape of the annuli is determined by the galaxy’s morphology. Each spectrum is shifted to rest frame wavelength before stacking using the velocity measurements obtained from pPXF. The spectra are then broadened to a reference velocity dispersion, \( \sigma \) (the maximum velocity dispersion of the galaxy). This reduces the dilution of the spectral features due to rotational broadening and allows us to have a fixed and constant velocity dispersion when measuring the stellar population parameters. The result is one spectrum per annulus per galaxy.

From the 10 BCGs and 4 companion galaxies presented in Jimmy et al. (2013), the BCG 1153, and the companion of BCG 1066 have too low SNR for stellar population analysis. The final sample thereby consists of 9 BCGs, 4 of them with close massive companions. For 2 of these (1027, 1048) it was possible to resolve the companions as well. In those cases the main galaxy is referred to as 1027A and 1048A, and the companions as 1027B, 1048B, and 1048C.

Figure 3.1 shows the annular distribution of 3 representative galaxies. The upper panels are the flux-collapsed VIMOS image. The lower panels are the annular distribution per galaxy. The annuli cover up to 1 \( R_e \) in each galaxy. The central aperture has been defined as 0.2 \( \pm \) 0.03 \( R_e \), allowing the central annulus to contain two or more spaxels (for most of the galaxies). The median value of the SNR of the final sample stacked spectra is \( \sim 35 \, \text{Å}^{-1} \) with the majority having SNR > 20 \( \text{Å}^{-1} \). Only the outermost annuli in the companion galaxies 1048B and 1048C drop below this threshold (SNR = 15 \( \text{Å}^{-1} \)).

The analysed rest wavelength range (3900-5600 \( \text{Å} \)) covers the absorption line indices: \( \text{Ca}_K \) (Ca II 3933), \( \text{Ca}_H \) (Ca II 3968), H\( \delta \), H\( \gamma \), \( \text{Ca}_G \) (Ca I 4307), H\( \beta \), Fe5015, Mgb5175, Fe5270. The age and metallicity measurements are based on the full spectrum fit. However, the weaker Balmer indices H\( \delta \), and H\( \gamma \) are masked to ensure a clean comparison.

\[\text{http://astronomy.swin.edu.au/~poliva/codes/annuli_stacking/spectra.py}\]
with the ATLAS$^3$D data (for which age measurements are based on H$\beta$). The enhanced lines Ca$_K$, Ca$_H$, and Ca$_G$ provide a strong case for the existence of old stellar populations. Furthermore, where there are mixed stellar populations, the ratio between these lines indicates the relative importance of the young stellar populations (Sánchez Almeida et al., 2012).

Figure 3.1: Three representative BCGs: 1050 (SR), 2039 (SR), 1261 (FR). Upper panels: The flux-collapsed VIMOS image ($27'' \times 27''$). Lower panels: The annular distribution for each galaxy. The central annulus, corresponds to the aperture $0.2 \pm 0.3$ $R_e$. The annuli all extend to 1 $R_e$.

3.4.1 Stellar Population Models

I use the stellar population models of Vazdekis et al. (2010), based on the MILES stellar library (Sánchez-Blázquez et al., 2006a), to estimate the ages and metallicities of galaxies in this sample. The Vazdekis et al. (2010) models use the Padova 2000 (Girardi et al., 2000) isochrones which cover a metallicity range of $[\text{Fe/H}] = [-1.7, 0.4]$ and ages $[2.1 \times 10^7, 1.7 \times 10^{10}]$ yr. After testing the spectra with the whole age range, the analysis

$^5[\text{Fe/H}] = \log_{10} (Z/Z_\odot)$, and $Z_\odot = 0.0189$ (Anders & Grevesse, 1989)
has been restricted to single stellar population sequences of $[1 \times 10^9, 1.7 \times 10^{10}]$ yr, divided into 40 age bins.

The stellar population models of PEGASE-HR (Le Borgne et al., 2004) coupled to the ELODIE (Prugniel et al., 2007) stellar library were also considered. These models are known for their high spectral resolution (0.55 Å) and for allowing the user to choose the initial mass function along with other physical ingredients. The PEGASE-HR wavelength coverage is consistent with these data, ($\lambda > 3900$ Å). Furthermore, the stellar library has the same age range as MILES. Both libraries give consistent metallicities and ages within 1σ uncertainties. However, the flux calibration of the MILES library over a wide spectral range is more appropriate for this spectral fitting of unresolved stellar populations. The average spectral resolution of MILES (2.3 Å) is also closer to that of the VIMOS observations (2.1 Å). This minimises information loss when broadening the observed spectra. Therefore, the Vazdekis et al. (2010) models are the most suitable for this analysis and are the ones used.

### 3.4.2 Full Spectrum Fitting

The most suitable technique to estimate the stellar population parameters is the full spectrum fitting technique (e.g., Koleva et al., 2008). This technique features some advantages over classical methods, i.e., the Lick/IDS system (e.g., Worthey & Ottaviani, 1997), as it exploits all the information contained in the spectra, pixel by pixel, independently of the spectrum shape. It also allows analysis at medium spectral resolutions ($< 3$ Å), in contrast to the Lick/IDS system which has a low spectral resolution, ($> 8.4$ Å). In this analysis, the STEllar Content and Kinematics via Maximum A Posteriori algorithm (STECKMAP; Ocvirk et al., 2006a,b) has been selected to extract the ages and metallicities from the spectra.

STECKMAP uses Bayesian statistics to estimate the stellar content of the spectra. It is based on a non-parametric formalism. The code returns a luminosity-weighted age and metallicity distribution. This comes from flux-normalising the stellar library (rather than mass normalisation). The results are a proxy to the star formation history of the galaxy. The method is regularised by a Laplacian kernel in order to avoid chaotic oscillations. To prevent systematic errors from poor flux calibration, the code produces a non-parametric transmission curve which represents the instrumental response multiplied by the interstellar extinction. Further the spectral region around the weak emission lines is masked, even
though they are not observed, so that they do not interfere with the stellar population model fitting (e.g. [NeIII] 3868.71, [OIII] 4959, 5007, [NI] 5198, 5200).

In order to obtain accurate, robust results first the spectrum is tested by measuring the stellar population parameters using two different age initial conditions: (a) a flat stellar age distribution. (b) a random Gaussian distribution of ages (see Ocvirk, 2011). Then the results from both runs are compared—expecting them to be consistent. If this test is successful, I proceed to calculate the final value of the stellar population parameters. The final estimated luminosity-weighted age and metallicity are the median values from 150 Monte Carlo realisations. In each Monte Carlo realisation the initial condition is a random Gaussian age distribution that is later refined through iterations until it reaches the best fit. The measurement uncertainties are the standard deviations of the 150 Monte Carlo realisations. Figure 3.2 shows the spectrum of the central annulus of 2039. The black line is the observed spectrum, the red line represents the best fit to the spectrum and the vertical dotted lines indicate the significant spectral features.

Unfortunately, steckmap, in conjunction with the MILES/ELODIE stellar libraries, has the disadvantage of being tied to solar abundance ratios ([α/Fe] = 0). High α-element [α/Fe] abundances are not included in this model. The effect of using [alpha/Fe] = 0 in elliptical galaxies and globular clusters is apparent at low metallicities ([Fe/H] < −0.7 dex) where the ages may be bias by ∼ 20 percent (Koleva et al., 2008). This can only be resolved when full spectral fitting stellar population models implement evolutionary tracks and [α/Fe] > 0. However, BGCs are not significantly affected by the limitation of the models. While they are [alpha/Fe] enhanced, their metallicities are in general above solar (e.g. von der Linden et al., 2007), which avoids biases in the age estimations. The following section explores the impact of this on the stellar population fits using a Lick index analysis.

3.4.3 Lick/IDS System

The stellar population parameters can also be estimated using the Lick/IDS system (e.g. Worthey & Ottaviani, 1997). This method measures the equivalent width of the absorption features at a fixed IDS resolution (> 8.4 Å) to later compare them with stellar population models that provide the corresponding age and metallicity values (e.g. Worthey & Ottaviani, 1997; Vazdekis et al., 1997; Proctor & Sansom, 2002; Schiavon, 2007).
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Figure 3.2: Rest wavelength spectrum of the central annulus of BCG 2039. The black line represents the observed spectrum, the red line shows the best fitting stellar populations from STECKMAP. The green line shows the residuals of the fit. The shaded regions show the regions that were masked on the fit. The major features are marked with dotted vertical lines. The recovered stellar populations are $[\text{Fe/H}]_{[\alpha/\text{Fe}]=0} = 0.13 \pm 0.01$ and Age = $9.6 \pm 1.0$ Gyr. The fit is a good match to the data.

To evaluate the robustness of the results obtained using STECKMAP I test the VIMOS spectra with the Lick/IDS system (see Figure 3.3). The stellar models and absorption lines selected are those used by the ATLAS$^{3D}$ team to measure the $[\alpha/\text{Fe}]$ abundances, ages and metallicities i.e. Schiavon (2007), H$\beta$, Fe5010, and Mgb. The uncertainties in ages and metallicities are propagated from the error on the Lick indices measurements (mean 0.1Å) and are computed from the chi-squared of the model grid. Figure 3.4 shows the central $[\alpha/\text{Fe}]$ of the BCGs (green-filled and red-open squares) and the ATLAS$^{3D}$ sample (blue crosses) as a function of mass. The BCG $[\alpha/\text{Fe}]$ values (median $[\alpha/\text{Fe}] = 0.17 \pm 0.04$) are consistent with those of the ATLAS$^{3D}$ massive galaxies (median $[\alpha/\text{Fe}] = 0.24 \pm 0.03$).

Figure 3.5 shows the estimated metallicities and ages from both methods, STECKMAP and Lick indices. The Lick ages (median Age = $10.0 \pm 1.1$ Gyr) and metallicities (median $[\text{Z/H}] = 0.18 \pm 0.02$) are consistent with those from STECKMAP (median Age = $8.9 \pm 3.3$ Gyr, median $[\text{Fe/H}]_{[\alpha/\text{Fe}]=0} = 0.13 \pm 0.07$) within 1σ error. The Lick indices have been corrected to the Lick resolution. The STECKMAP results are also consistent with the stellar populations analysed by Gallazzi et al. (2005) from the SDSS DR4 spectra (of the galaxies...
The final results presented from this point use the stellar population parameters measured with STECKMAP.

Figure 3.3: Lick indices as a function of velocity dispersion. The squares represent the BCGs and the blue crosses represent the ATLAS$^3D$ galaxies. The indices were measured at a Lick/IDS resolution ($> 8.4$ Å). The BCGs show higher Hβ and Fe5010, and similar Mgb values than the early-type galaxies at fixed velocity dispersion.
3.5. Results

Here the main results from the BCG stellar population analysis.

3.5.1 Central Stellar Populations

The stellar population measurements come from a luminosity-weighted distribution, therefore the results are sensitive to the brightest and youngest population of stars in the galaxy (e.g., Trager & Somerville 2009). The central values are measured in an aperture of 0.2 ± 0.03 Re and are given in Table 3.2. 6 out of 9 BCGs (67 per cent of the sample) have central intermediate ages (5 < Age < 10 Gyr), and 3 out of 9 (33 per cent of the sample) are centrally old (Age > 11 Gyr). The median central age is 8.9 ± 3.3 Gyr. The BCGs have homogeneous super-solar metallicities (median [Fe/H] = 0.13 ± 0.07) in their central regions.
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Figure 3.5: Comparison between STECKMAP and Lick estimated stellar populations. The green-filled squares represent the central stellar populations of the SR BCGs and the red-open squares represent the FR BCGs. The line shows the one-to-one relationship. The $[\text{Fe/H}]_{\alpha/\text{Fe}=0}$ is equivalent to $[\text{Z/H}]$ (see Section 3.3). The uncertainties from the Lick estimated ages and metallicities are propagated from the error on the Lick indices measurements (mean 0.1Å) and are computed from the chi-squared of the model grid. The uncertainties in the STECKMAP measurements are the standard deviation from 150 MCMC iterations. The STECKMAP and Lick measurements agree within 1σ error.

Figure 3.6 shows the central metallicities (upper panel) and ages (lower panel) as a function of galaxy mass. The SR and FR BCGs are presented as green-filled squares and red-open squares respectively. The companion galaxies (all FRs) are shown as open stars. There are no significant differences between the SRs and FRs, consistent with McDermid et al.
The crosses represent the central stellar populations of the early-type galaxies in the ATLAS$^{3D}$ sample (McDermid et al., 2015). From a Kolmogorov - Smirnov (K-S) test, the hypothesis that the massive early-type galaxy metallicities and BCG metallicities come from the same distribution, cannot be rejected at a 11 per cent confidence level (P-value 0.11). The BCGs have similar central metallicities (median $[\text{Fe}/\text{H}]_{[\alpha/\text{Fe}]=0} = 0.13 \pm 0.07$) to early-type galaxies in ATLAS$^{3D}$ (median $[Z/\text{H}] = 0.04 \pm 0.07$) at fixed mass.

The BCGs have slightly younger central ages (median Age $= 8.9 \pm 3.3$ Gyr) compared to the ATLAS$^{3D}$ galaxies at the same mass (median Age $= 12.0 \pm 3.8$ Gyr). From a K-S test the age distribution of early-type galaxies and BCGs are different (P-value $1.2 \times 10^{-6}$). Also the BCGs have similar central stellar populations to the companion galaxies.

In summary, the sample BCGs show homogeneous central metallicities and a wide range of ages. They show similar metallicities to other early-type galaxies of similar mass.

Table 3.2 : Central stellar populations of BCGs and their companions.

<table>
<thead>
<tr>
<th></th>
<th>Galaxy</th>
<th>log [Fe/H]</th>
<th>log [Fe/H] error</th>
<th>Age (Gyr)</th>
<th>Age error (Gyr)</th>
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<td>BCG SR</td>
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<td>0.18</td>
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<td>1.1</td>
</tr>
<tr>
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<td></td>
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<td>0.048</td>
<td>8.9</td>
<td>1.1</td>
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<td>0.08</td>
<td>5.4</td>
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<td>0.079</td>
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<td>1.2</td>
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</table>

Note: The errors given are the measurement uncertainties (from the standard deviation of 150 MCMC realisations).
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Figure 3.6: Central stellar populations as a function of dynamical galaxy mass. The SR BCGs are shown as green-filled squares. The FR BCGs are shown as red-open squares. The FR companion galaxies are shown as open stars. The error bars represent the standard deviation of 150 MCMC realisations. The blue crosses represent the central stellar populations of the early-type galaxies in the ATLAS$^{3D}$ sample. The blue-filled circle is the BCG M87 from the ATLAS$^{3D}$ sample. The dashed line shows the mass range ($M_{\text{dyn}} > 10^{11.3} M_\odot$) used in the comparison between the two samples. **Upper panel:** Central metallicities as a function of dynamical galaxy mass. The BCGs show similar metallicities (median $[\text{Fe/H}]_{\alpha/Fe}=0=0.13 \pm 0.07$) compared to the ATLAS$^{3D}$ galaxies at the same mass (median $[Z/H ]= 0.04 \pm 0.07$). **Lower panel:** Central ages as a function of mass. The BCGs central ages (median Age = $8.9 \pm 3.3$) are consistent with the ages of the ATLAS$^{3D}$ galaxies of the same mass (median Age = $12.0 \pm 3.8$) within 2$\sigma$ error. The central stellar populations of BCGs show little scatter or dependence on their angular momentum.

3.5.2 Age and Metallicity Profiles

The stellar population gradients and their uncertainties are measured using a linear log-log chi-squared fitting routine. The uncertainties are the standard deviation of the fit. The stellar population gradients ($\Delta [\text{Fe/H}]$ and $\Delta$ Age) are given in Table 3.3. The metallicity and age profiles for the BCGs and companion galaxies are illustrated in Fig-
Most of the BCGs in the sample have shallow metallicity gradients, $\Delta[\text{Fe/H}] > -0.3$, except for 1066 which has a gradient of $\Delta[\text{Fe/H}] = -0.41 \pm 0.1$. The median value is $\Delta[\text{Fe/H}] = -0.11 \pm 0.1$. The companion galaxies also show shallow metallicity gradients. However, 1048B and 1048C have $R_e$ values close to the seeing FWHM, which may act to dilute the measured gradient in these galaxies.

The stellar population gradients observed for the BCGs are summarised in Figure 3.10. The gradients are compared to those of SAURON galaxies in the same mass range. The offset between the two profiles illustrates the differences between the central stellar populations in the two samples.

Figure 3.11 shows the metallicity (upper panel) and age (lower panel) gradients as a function of galaxy mass. The BCGs have shallow metallicity (median $\Delta[\text{Fe/H}] = -0.11 \pm 0.1$) and age gradients (median $\Delta\text{Age} = 0.02 \pm 0.03$), similar to those of the SAURON early-type galaxies at the same mass ($\Delta[\text{Fe/H}] = -0.19 \pm 0.1$, $\Delta\text{Age} = 0.04 \pm 0.05$). There is no correlation between the stellar kinematics and the stellar population gradients.

### Table 3.3: Stellar population gradients of BCGs and their companions.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>$\Delta[\text{Fe/H}]$</th>
<th>$\Delta[\text{Fe/H}]$ error</th>
<th>$\Delta\text{Age}$</th>
<th>$\Delta\text{Age}$ error</th>
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</tr>
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</tr>
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<td></td>
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</tr>
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<td>0.133</td>
</tr>
<tr>
<td>Comp</td>
<td>median</td>
<td>-0.110</td>
<td>0.160</td>
<td>0.133</td>
</tr>
</tbody>
</table>

*Note: The errors given are the measurement uncertainties (the standard deviation of the fit).*
Chapter 3. Stellar populations of BCGs

Figure 3.7: Metallicity (upper panel) and age (lower panel) profiles of the SR BCGs. The name of the galaxy can be found in the upper-left corner. The gradient values are shown in the lower-right corner along with the errors in the fit. The shaded area represents the seeing FWHM (0.9″). Each green square represents the metallicity and age value of each annulus in the galaxy. The dotted line represents the best fit to the profile. The dashed line indicates the central region (an aperture of 0.2 $R_e$). The SR BCGs have a large scatter in their observed metallicity and age gradients.

3.6 Discussion

BCGs represent the extremely massive end of the early-type galaxy population. These galaxies live in high-density environments commonly surrounded by many companions. This chapter has presented here the first integral field analysis of the radial stellar populations of 9 BCGs up to 1 $R_e$. 
3.6. Discussion

Figure 3.8: Metallicity (upper panel) and age (lower panel) profiles of the FR BCGs. The name of the galaxy can be found in the upper-left corner. The gradient values are shown in the lower-right corner along with the errors in the fit. The dotted line represents the best fit to the profile. The dashed line indicates the central region (an aperture of 0.2 R_e). The shaded area represents the seeing FWHM (0.9”). Each red-open square represents the metallicity and age value of each annulus in the galaxy. Both of the FR BCGs have negative metallicity gradients and positive age gradients.

3.6.1 Stellar Ages

Hydrodynamical simulations of early-type galaxies (in less dense environments than BCGs) predict more massive galaxies to be older than less massive galaxies, such that at masses > 10^{10.5} M_☉ the galaxies are older than 10 Gyr (e.g. Naab et al. 2014; Peeples et al. 2014; Hirschmann et al. 2013) and show passive evolution from z = 2. 3 out of 9 BCGs in this sample have old central ages (> 12 Gyr), in agreement with this prediction. These 3 galaxies are also consistent with the massive early-type galaxies from ATLAS3D (median Age = 12.0 ± 3.8 Gyr).

However, 6 out 9 sample BCGs have central intermediate ages (5 ≤ Age < 10 Gyr). Previous observations have shown that these intermediate ages in BCGs are not unusual. Loubser et al. (2009) analysed a large sample of 49 BCGs, and found that 24 of them (49 per cent of the sample) are younger than 9 Gyr old. Fitzpatrick & Graves (2014) found that, at fixed velocity dispersion and surface brightness, central galaxies in SDSS are younger than satellite galaxies. La Barbera et al. (2014) also found that central galaxies have younger ages and higher metallicities than isolated early-type galaxies. Consistently, these 6 BCGs sit at the younger age limit of the massive early-type galaxies from ATLAS3D.
Figure 3.9: Metallicity and age profiles of the companion galaxies (all FRs). Each double panel shows the metallicity (upper panel) and age (lower panel) profiles of each companion. The name of the galaxy can be found in the upper-left corner. The dotted line represents the best fit to the profile. The gradient values are shown in the lower-right corner along with the errors in the fit. The dashed line delimitates the central region (an aperture of 0.2 $R_e$). The shaded area represents the seeing FWHM (0.9’). Each open star represents the metallicity and age value of each annulus in the galaxy. All 3 of them have a flat metallicity gradient. However, in 1048B and 1048C, this could be a result of the seeing FWHM being equivalent to the $R_e$ in these galaxies.

Many hypotheses have tried to explain why such massive galaxies as BCGs have intermediate age stellar populations. A common prediction is that gas cooling from the intra-cluster medium may be forming stars which will result in young ages (e.g. Edwards et al., 2007; O’Dea et al., 2008; Bildfell et al., 2008; Loubser, 2014). For most of the clusters considered here, X-ray imaging is not available, thus is not possible to assess whether they host a cool core or not. Only two of the BCGs have been confirmed to be hosted by a non-cooling flow cluster (White et al., 1997) and for those the results are contradictory: 2001 is one of the oldest galaxies in the sample, consistent with the cool core hypotheses, however, 1066 shows a young central region and a positive age gradient, suggesting that current cool cores are not the only possible explanation for the intermediate ages observed.

The semi-analytical model of Tonini et al. (2012) focuses on BCGs rather than on the general population of early-type galaxies, predicting that BCGs have more prolonged star formation as a result of their active merger history. The BCGs experience continuous bursts of star formation across cosmic time, generating many stellar populations super
3.6. Discussion

Figure 3.10: Stellar population profiles of BCGs and early-type galaxies of similar mass. The solid lines represent the median stellar population gradients of the sample BCGs. The dashed lines represent the median stellar population gradients of the most massive galaxies in the SAURON sample (Kuntschner et al., 2010). The grey (BCGs) and blue (SAURON) shaded regions indicate the error on the median. These values are specified in each panel. BCGs and early-type galaxies at the same mass have similar age gradients and their metallicity gradients are within 2σ error.

imposed on one another. The age measurements here are luminosity-weighted, which means they reflect the youngest stellar population of the galaxy. Therefore, the intermediate ages found here suggest that the last star formation event could have taken place at $z \sim 1$ when galaxy mergers are more likely to be gas rich.

3.6.2 Metallicities

The BCGs in the sample show very homogenous central metallicities (median $[\text{Fe/H}]_{[\alpha/\text{Fe}]=0} = 0.13 \pm 0.07$). These high metallicities are consistent with previous long-slit and fibre observations of BCGs (Brough et al., 2007; von der Linden et al., 2007; Loubser et al., 2009; Eigenthaler & Zeilinger, 2013) and are in agreement with the hypothesis of continuous star formation events at high redshifts.

The sample BCGs have a range of metallicity gradients, from flat to shallow (median
Chapter 3. Stellar populations of BCGs

Figure 3.11: Metallicity (upper panel) and age (lower panel) gradients as a function of dynamical galaxy mass. The SR BCGs are shown as green-solid squares. The FR BCGs are shown as red-open squares. The error bars represent the standard deviation of the fit. The blue dots represent the galaxies in the SAURON sample (Kuntschner et al., 2010). The blue-filled circle is the BCG M87 from the SAURON sample. The dotted line indicates a flat gradient. The dashed line shows the mass range ($M_{\text{dyn}} > 10^{11.5}M_\odot$) used in the comparison between the two samples. The BCGs (median $\Delta[\text{Fe/H}] = -0.11 \pm 0.1$) and the most massive early-type galaxies (median $\Delta[\text{Fe/H}] = -0.19 \pm 0.1$) have similar stellar population gradients.

\[ \Delta[\text{Fe/H}] = -0.11 \pm 0.1 \text{ similar to other massive early-type galaxies at similar mass (} \Delta[Z/H] = -0.19 \pm 0.1; \text{ Figure 3.11).} \]

Hydrodynamical simulations predict that galaxies that form through dissipative core collapse have typical metallicity gradients $\Delta[\text{Fe/H}] \sim -0.4$ (e.g. Kobayashi, 2004; Hirschmann et al., 2015). This is significantly steeper than the gradients of these BCGs. However, simulations also show that this initial gradient can later be affected by mergers (Hirschmann et al., 2013; Martizzi et al., 2014).

Dissipationless major mergers make the stars lose their orbits and move randomly within
3.6. Discussion

the distribution of the galaxy, inducing stellar population mixing and flattening the gradients (Hopkins et al., 2009). This suggests that the BCGs as well as the massive SAURON galaxies have gone through at least one dissipationless major merger since $z < 1$ (Kobayashi, 2004; Hirschmann et al., 2015).

3.6.3 Merger Histories

The main conclusion of this analysis is that BCGs have diverse evolutionary paths. 3 out of 9 BCGs in the sample show old and metal-rich central stellar populations, and shallow metallicity gradients. This suggest that their stars were formed in-situ at $z > 2$. Thereafter the galaxies grow in mass and size by at least one major merger and many minor mergers (e.g. Kobayashi, 2004; Hirschmann et al., 2015). These galaxies are similar to the massive early-type galaxies in the SAURON and ATLAS3D sample which also have old central stellar populations and shallow metallicity gradients.

The rest of the sample (6 out of 9) BCGs have intermediate central ages, high central metallicities, and shallow metallicity gradients in BCGs. This implies that these galaxies have experienced active accretion histories throughout cosmic time, as predicted by semi-analytical and dark matter simulations (De Lucia & Blaizot, 2007; Tonini et al., 2012; Laporte et al., 2013). The dense environment where BCGs evolve allows them to experience many mergers. These mergers will trigger star formation at high redshifts, and will disrupt the metallicity gradients at $z < 1$, given that the fraction of gas in the merging galaxies decreases with time.

Jimmy et al. (2013) found that 4 of the 9 BCGs studied here show photometric signatures of minor mergers. The effect of minor mergers are not apparent in the inner ($< 1 R_e$) stellar population gradients studied here, as minor mergers only affect stellar population gradients at $> 2 R_e$ (Foster et al., 2009; Barbera et al., 2012; Pastorello et al., 2014; Hirschmann et al., 2015). However, the photometric results are evidence of the active merging activity of these galaxies. Furthermore, 4 of the galaxies in the sample have close massive companions, most of these companions are FRs and are gravitationally bound to their respective BCG. This suggests a potential future major merger (Jimmy et al., 2013).

Many studies have found similar results on the stellar populations of BCGs (e.g. Whiley et al., 2008; Stott et al., 2008). Wen & Han (2011) analysed the BCGs colours from different high-redshift data sets (CFHT, COSMOS, SWIRE) and found that BCGs are
consistent with stellar population synthesis models in which the galaxy formed at \( z > 2 \). However, a large fraction of the sample shows bluer colours on the \( g' - z' \) and \( B - m_{\mu m} \) bands at \( z \sim 0.8 \), indicating star formation at those epochs. Furthermore, some BCGs show low levels of star formation in the local Universe (e.g. Liu et al., 2012; Oliva-Altamirano et al., 2014; Fraser-McKelvie et al., 2014). This is consistent with the hypothesis that BCGs have complex accretion scenarios.

Thanks to the spatial extent of the IFS it was possible to resolve 3 companion galaxies (1027B, 1048B, 1048C) from 2 of the BCGs (1027A, 1048A). The companion galaxies have similar stellar populations to their respective BCGs. However, due to the fact that their effective radii are close to the seeing FWHM, their stellar population gradients are unreliable.

### 3.6.4 Connection Between Stellar Populations and Kinematics

One of the advantages of using IFS for this analysis is that we can compare the stellar populations to the kinematics of the galaxies in the sample. Here have been analysed 7 slow and 2 fast rotating BCGs have been analysed and their kinematics appear to be independent of their stellar populations. There is no correlation between the angular momentum of the galaxies and their stellar population gradients in this small sample. The SRs show a large scatter in their metallicity gradients. The 2 FRs have similar metallicity gradients, but within the range of the SRs.

Moody et al. (2014) and Naab et al. (2014) showed that if the gas fraction in a major merger is less than 10 per cent (dissipationless), the galaxy tends to maintain the slow or fast rotation of their progenitors. The BCGs in the sample are likely to have preserved the slow or fast rotation of their progenitors, given the lack of gas observed at present epochs and the evidence of recent dissipationless major mergers.
3.7 Conclusions

This Chapter presents the first analysis of the stellar populations of 9 BCGs using IFS observations. Their stellar populations are compared to those of the IFS observations of field early-type galaxies from the SAURON and ATLAS$^{3D}$ sample, drawing the following conclusions:

(1) The BCGs have a wide range of stellar ages, high metallicities, and have shallow metallicity gradients. This implies diverse evolutionary paths (passive and active accretion). The BCGs’ central stellar populations and gradients are consistent with those of early-type galaxies of similar mass, with the exception that the BCGs have a wide range of central ages.

(2) Three of the BCGs have similar mass close companions galaxies within 18 kpc. The companion galaxies have central stellar populations consistent with their respective BCG.

(3) There is no relationship between the stellar populations of BCGs and their stellar kinematics (slow and fast rotators).

IFS analysis allowed us to determine the angular momentum of BCGs and to study their stellar population gradients without the orientation bias innate to long-slit spectroscopy. It has also allowed us to include their companion galaxies in the analysis. This study hints of intriguing differences between BCGs and similar mass early-type galaxies but requires much larger samples to confirm. The SAMI galaxy survey [Bryant et al. 2015] currently underway will allow us to achieve this goal. New ultra wide-field IFSs such as MUSE on the Very Large Telescope and large date sets as the MASSIVE survey [Ma et al. 2014] will also allow us to determine whether the picture is different at radii beyond 1 $R_{e}$. 
4

The role of environment on the angular momentum of BGG/BCGs

_Brightest group and cluster galaxies (BCGs) are predicted to be highly dependent on their host environment. This Chapter presents the first analysis of the influence of galaxy stellar mass and cluster environment on the angular momentum of 29 BCGs at $0 < z < 0.2$. This includes new integral-field observations of 12 BCGs. These galaxies span a wide range of stellar masses ($10 < \log(M_*/M_\odot) < 11.8$) and halo masses (from groups to clusters, $12 < \log(M_{200}/M_\odot) < 15.5$). I explore here the stellar – cluster halo mass relationship and its role on BCG angular momentum._

—Oliva-Altamirano et al., submitted to MNRAS

4.1 Introduction

The central galaxies of groups and clusters are commonly the brightest galaxies (BCGs). These galaxies sit at the extreme end of the galaxy mass distribution. Simulations show that BCGs have higher merger rates than less massive early-type galaxies (White & Rees, 1978; Khochfar & Burkert, 2003; De Lucia & Blaizot, 2007; Oser et al., 2010; Tonini et al., 2012; Laporte et al., 2013). The main reason for this is their privileged position at the bottom of the gravitational potential of the cluster.

Stellar kinematics can be used to examine the merger history of galaxies. Initial analyses of BCGs used long-slit spectroscopy to quantify their stellar velocity and velocity dispersion profiles (e.g. Fisher et al., 1995; Carter et al., 1999; Brough et al., 2007; Loubser et al., 2008). Integral Field Spectroscopy (IFS) now allows observations which combine

1Throughout this chapter BCG refers to the brightest galaxy closest to the centre of the group or cluster. I make no distinction between groups and clusters to give continuity to the analysis.
spectral with spatial information. The SAURON (de Zeeuw et al., 2002) and ATLAS$^{3D}$ (Cappellari et al., 2011) IFS surveys introduced the $\lambda_R$ parameter as a proxy for the specific angular momentum of galaxies and classify them as fast (high angular momentum) or slow (low angular momentum) rotators.

Several simulations have tried to explain the final angular momentum of a galaxy through its merger history (e.g. Bois et al., 2011; Khochfar et al., 2011; Naab et al., 2014). A favoured scenario is where slow rotators have gone through 1 to 5 major mergers, with their last dissipational merger at $z > 1$, and more recently they have undergone many dry minor mergers (Krajnović et al., 2011; Bois et al., 2011; Khochfar et al., 2011). In contrast, fast rotators appear to be the result of major mergers involving high fractions of gas (Naab et al., 2014). However, observations and simulations do not completely agree yet. Observations instead concluded, that fast rotators are the result of mergers involving quenched spiral galaxies (Cappellari et al., 2011, 2013b).

BCGs are the perfect laboratory to test these merger scenarios. McGee et al. (2009) found that around 40 percent of the cluster galaxy population has been accreted from galaxy groups, and BCGs play a special role in this assembly. When a cluster merges with another cluster or group, the central galaxy tends to accrete the most massive galaxies of the in-falling halo (e.g. Balogh & McGee, 2010; De Lucia et al., 2012) due to dynamical friction. It is expected that the majority of BCGs would have low angular momentum as they are the end product of the hierarchical scenario (van Dokkum et al., 2010). Unfortunately, there are too few IFS observations of the stellar kinematics of BCGs to probe this hypothesis, particularly of BCGs in low mass halos (groups).

Jimmy et al. (2013) studied the stellar kinematics of 10 BCGs (in clusters with $\log(M_{200}/M_\odot) > 13.7$). They found that the majority of the galaxies (70 percent) are slow rotators, however, 30 percent of the sample are fast-rotating. They also found that the current angular momentum of these BCGs was not correlated with recent (less than 0.2 Gyrs ago) minor mergers.

Aside from Jimmy et al. (2013), the only IFS observations of the stellar kinematics of BCGs are those dedicated to analysing the kinematic morphology – density relationship in clusters (D’Eugenio et al., 2012; Houghton et al., 2013; Scott et al., 2014; Fogarty et al., 2014). The BCGs in the Virgo (Emsellem et al., 2011), Fornax (Scott et al., 2014), Coma
4.1. Introduction

(Houghton et al., 2013), Abell 1689 (D’Eugenio et al., 2012) and Abell 85 and 168 (Fogarty et al., 2014) clusters are slow rotators. The three brightest galaxies in Abell 2399 (Fogarty et al., 2014) are fast rotators. Also one of the two brightest galaxies in Abell 168 is a fast rotator. The overall percentage of slow rotators in BCGs across these heterogeneous studies is \( \sim 70 \) percent. However, none of these studies have examined the lower mass, group, environment. Therefore, the angular momentum of central group galaxies is still unknown, and the role of environment is yet to be studied.

The cluster environment can also be parametrised by the dominance of the cluster (\( \Delta m_{1,2} \)). This refers to the magnitude gap between the brightest and the second brightest galaxy in a cluster (Tremaine & Richstone, 1977b; Loh & Strauss, 2006; Smith et al., 2010). The dominance has been used together with X-ray luminosities to identify clusters thought to have formed at early epochs (Proctor et al., 2011; Harrison et al., 2012). Small magnitude gaps (\( \Delta m_{1,2} < 1 \)) could indicate that the cluster has recently gone through a cluster – cluster merger (e.g. Smith et al., 2010; Dariush et al., 2010; Coenda et al., 2012; Martel et al., 2014). These cluster-cluster mergers are likely to affect the angular momentum of BCGs. However, due to the small numbers observed to date this has not yet been explored.

Cappellari et al. (2013b) and Cappellari (2013c) examined the influence of the size – stellar mass relationship on the angular momentum of the galaxies within the ATLAS\(^{3D} \) sample (field and cluster galaxies from the Virgo cluster) adding further observations from the Coma clusters. The transition between fast and slow rotators suggests a connection with the mass – size relationship, particularly in cluster environments. A fast rotator evolves into a slow rotator while the size of the galaxy increases proportionally with stellar mass. Cappellari (2013c) defines a critical stellar mass \( \log(M_{*, \text{crit}}/M_{\odot}) = 11.3 \) above which the majority of galaxies are slow rotators with no horizontal elongation in the velocity maps.

It is not clear whether BCGs behave similarly to the early-type galaxies in the ATLAS\(^{3D} \) sample, or whether they follow a different relationship with mass and size. Cappellari (2013c) only included the BCGs in the Virgo and Coma clusters. To study the influence of the size – mass relationship on the angular momentum of BCGs it is necessary to observe a larger sample than that available to date.
Here the sample of BCGs observed with IFS to date [Brough et al., 2011; Jimmy et al., 2013; D’Eugenio et al., 2013; Houghton et al., 2013; Scott et al., 2014; Fogarty et al., 2014; Emsellem et al., 2014], is expanded by adding 12 BCGs, observed with the SPIRAL IFS on the Anglo-Australian Telescope. These galaxies span a wide range of halo masses (from group to cluster, $12 < \log(M_{200}/M_\odot) < 15.5$) and stellar masses ($10 < \log(M_*/M_\odot) < 11.8$). This is the first analysis of the effect of the cluster environment and galaxy mass on the angular momentum of BCGs. I explore the relationship of the specific angular momentum with galaxy stellar mass and size, cluster halo mass and dominance.

4.2 Observations and Data Reduction

The galaxies in these new observations are the brightest galaxies closest to the centre of their host group or cluster. The new observations presented here are 12 BCGs selected from two different catalogues. The selection criteria were the following: a) Effective radius between 2 and 6 arcsec, to fit within the field-of-view; b) Redshift range $0.02 < z < 0.22$, to ensure good signal-to-noise (SN); c) Right Ascension from 175 to 325 deg (J2000). These galaxies are of similar morphology (Sérsic indices $3.9 \pm 0.6$) and are representative of the range of halo masses (group multiplicity $\geq 5$; Figure 4.1).

C4 Cluster Catalogue [Miller et al., 2005; von der Linden et al., 2007]. This catalogue includes 625 BCGs at $z < 0.1$ from the Third Data Release of the Sloan Digital Sky Survey (SDSS; York et al., 2000). The BCG in this catalogue is defined as the brightest galaxy closest to the deepest point of the potential well (von der Linden et al., 2007). I have selected 5 galaxies from this catalogue, in halos with masses $12.6 < \log(M_{200}/M_\odot) < 14.5$ (Figure 4.1 dotted lines). To simplify, I identify each galaxy from the C4 catalogue by the initials C4 and their last 4 numbers i.e. C4 2121 instead of SDSS-C4-DR3-2121.

The Galaxy Group Catalogue (G3C version v04; Robotham et al., 2011). The G3C uses an adaptive friends-of-friends algorithm to identify groups and clusters in the Galaxy And Mass Assembly (GAMA [Driver et al., 2011] survey². GAMA is a multi-wavelength survey, with optical spectra observed from the Anglo-Australian Telescope. The galaxies in the sample were selected from GAMA I (the first phase of the survey), which covers three equatorial regions of the sky ($\sim 144$ deg²). GAMA I includes observations of $\sim 170,000$ galaxies spanning a wide range of redshifts (mean $z \sim 0.2$) with a spectroscopic completeness of $\sim 97$ percent. The BCG in this catalogue is defined as the brightest galaxy in

²http://www.gama-survey.org/
4.2. Observations and Data Reduction

Figure 4.1: Distribution of cluster halo mass for the G$^{3}$C (grey histogram; Robotham et al., 2011) and C4 (open histogram; Miller et al., 2005) catalogues. Each vertical line represents one cluster in the observed sample. The clusters selected from GAMA (G$^{3}$C catalogue) are shown as dashed lines and the clusters selected from the SDSS (C4 catalogue) are shown as dotted lines. These BCGs represent a wide range of cluster environments.

the $r$-band within the group. The centre of the group is defined by a luminosity-weighted iteration (Robotham et al., 2011). I have selected 7 galaxies from GAMA. All of them are BCGs coinciding with the spatial centroid of their host group. These are in halos with masses $12 < \log(M_{200}/M_\odot) < 14.5$ (Figure 4.1 dashed lines). The galaxies in GAMA are identified by the initial G and a set of 5 to 6 numbers (the GAMA CATAID).

In the following sections I describe the observation and data reduction of the 12 new galaxies observed for this analysis. The galaxies are illustrated in Figure 4.2.

4.2.1 Observations

The 12 new BCGs presented here were observed using the SPIRAL integral-field unit. SPIRAL was an instrument on the 3.9m Anglo-Australian Telescope at the Siding Spring Observatory, feeding the AAOmega spectrograph (Sharp et al., 2006). SPIRAL was composed of 512 fibres arranged in a rectangular array of $32 \times 16$ with a spatial sampling of 0.7 arcsec spaxel$^{-1}$ and a resulting field-of-view (FOV) of 22.4 arcsec $\times$ 11.2 arcsec.

These galaxies have been observed over 8 dark nights in May 2012. The AAOmega spectrograph has two arms, blue and red, separated by a dichroic beam splitter. I used both
the 570nm and 670nm dichroics available. While I observed each galaxy with both blue and red arms, in this analysis I focus on data from the blue arm. Throughout the run I used the low resolution 580V grating which has an average spectral resolution of R~1900. Depending on the dichroic used, the central wavelength varies from 480nm to 570nm. The average seeing was \(~1.1\) arcsec. Each object was observed in 5 to 7 frames of 2400 seconds each with individual observations dithered by 1-2 spaxels in Right Ascension and Declination in order to avoid the dead elements in SPIRAL. Spectrophotometric standard stars were also observed each night. The details of the observations are summarised in Table 4.1.
4.2. Observations and Data Reduction

Table 4.1: Observations. The galaxies are sorted by decreasing halo mass (see Section 4.3.3). The name corresponds to the C4 or GAMA ID. The exposure time shows the number of frames $\times$ seconds of exposure per frame.

<table>
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<th>Name</th>
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<th>DEC deg</th>
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<th>Exposure Time [sec]</th>
<th>Dichroic [nm]</th>
<th>Seeing [arcsec]</th>
<th>z</th>
<th>log $M_{200}$ $\pm 0.4 \ [M_\odot]$</th>
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<tr>
<td>C4 2216</td>
<td>324.0418</td>
<td>-8.2213</td>
<td>21 May 2012</td>
<td>5$\times$2400</td>
<td>670</td>
<td>0.9</td>
<td>0.085</td>
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</tr>
<tr>
<td>C4 2074</td>
<td>314.9754</td>
<td>-7.2607</td>
<td>18 May 2012</td>
<td>4$\times$2400</td>
<td>570</td>
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<tr>
<td>C4 2055</td>
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<td>-7.5921</td>
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</tr>
<tr>
<td>G 48560</td>
<td>217.5849</td>
<td>-0.6367</td>
<td>19/20 May 2012</td>
<td>6$\times$2400</td>
<td>570</td>
<td>1.3</td>
<td>0.131</td>
<td>12.27</td>
</tr>
</tbody>
</table>
Chapter 4. Angular momentum of BGG/BCGs

Figure 4.2: SDSS images of the galaxies. The galaxies are sorted by halo mass (from top to bottom: most massive to least massive halos). The blue square represents the SPIRAL FOV (11.2 × 22.4 arcsec$^2$).

4.2.2 Data reduction

To reduce the raw data I use the most recent version of the AAOmega pipeline, 2DFDR$^3$ (Sharp et al., 2006) version 6.00 (Rockhopper). The process begins by extracting the wavelength through the flat and arc-lamp frames. The root-mean-square dispersion around the wavelength solution is 0.12Å. The dispersion around the 5577Å skyline is 0.09Å. Twilight sky observations are used to provide a relative transmission correction across the IFS, after quartz-halogen flat fields have been used to remove the pixel-to-pixel response variations spectrally. Sky spectra are generated from fibres at the outer edges of SPIRAL not contaminated by galaxy light. The cosmic rays and other spectral defects are rejected with a sigma-clipping mean.

Once the individual science spectra have been extracted using 2DFDR, custom IDL routines are used to create the science cubes, the ‘x’ and ‘y’ axes contain the spatial coordinates and the ‘z’ axis contains the spectra. I combined all the frames per object by averaging each spaxel (spatial pixel). The frames were aligned using the telescope offset. This was inspected visually with the IDL routines. The bad pixels are set as flux = 0 to avoid any

4.3. Analysis

interference with the stacking process. As a result I have one data cube per galaxy with its associated science and variance extensions.

4.2.3 Stellar kinematics from previous observations and simulations

I add to the 12 new BCG observations a sample of 10 BCGs previously analysed in Brough et al. (2011, stellar kinematics), Jimmy et al. (2013, stellar kinematics) and Oliva-Altamirano et al. (2015, stellar populations). These BCGs were observed with VIMOS (Le Fèvre et al., 2003) on the Very Large Telescope in Chile, and are also selected from the SDSS C4 cluster catalogue (Miller et al., 2005). The sample spans a range of stellar masses $10^9 < \log(M_\star/M_\odot) < 11.6$, a cluster mass range of $13.7 < \log(M_{200}/M_\odot) < 15.3$, and redshifts $z < 0.1$. The new observations extend this existing sample to lower stellar and cluster masses.

I also include the stellar kinematics of the BCGs in the Virgo (M49; Emsellem et al., 2011), Fornax (NGC 1399; Scott et al., 2014), Coma (GMP2921 (NGC 4889); Houghton et al., 2013), Abell 1689 (12; D’Eugenio et al., 2012) and Abell 85, 168, and 2399 (019, 042, 086; Fogarty et al., 2015). These studies all used pPXF to calculate their velocity and velocity dispersions.

Recently, Martizzi et al. (2014) used a hydrodynamical zoom-in adaptive mesh refinement simulation including AGN feedback to study BCG angular momentum. They found a fraction of fast rotators similar to that found in Jimmy et al. (2013, ~ 30 percent). I show these simulated galaxies in the relevant figures throughout the paper.

4.3 Analysis

The main purpose of this work is to analyse the influence of galaxy structure (size and stellar mass), and environment (as measured by cluster halo mass and dominance) on the angular momentum of BCGs. The following sections describe the different measurements used in the analysis.

4.3.1 Photometric measurements: effective radii

It is essential to know the effective radius (the radius that contains 50 percent of the light, $R_e$) in order to accurately compare the angular momentum of the observed galaxies with previous observations. The $R_e$ of the galaxies selected from the GAMA survey (7/12) has
already been measured by Kelvin et al. (2012). They fit a two-dimensional Sérsic model to re-processed SDSS Data Release Seven r-band images. This procedure involves a series of astronomy software packages: Source Extractor (Bertin & Arnouts 1996), PSF Extractor and GALFIT 3 (Peng et al. 2010), all combined in a single code called SIGMA.

I manually calculate the $R_e$ of the galaxies selected from the C4 catalogue (5/12) using the same method as Kelvin et al. (2012). I first feed the r-band SDSS images into SExtractor to identify the different objects in the image. This provides the central pixel of each object, as well as an empirical $R_e$, magnitude, and orientation of the galaxy. In a second step, I run GALFIT on the r-band SDSS image using the values from SExtractor as a first guess. I use the -noskyest flag to let GALFIT calculate the sky level. The galaxies are fitted with a Sérsic profile ($n \sim 3 - 6$). To account for contamination from nearby galaxies I use object masking and simultaneous fitting. The accuracy is checked by inspecting the residuals of the fit. To confirm the technique I also use this method on the GAMA selected galaxies, and find the measurements to be consistent with those of Kelvin et al. (2012) maximum difference of $R_e$,this work - $R_e$,Kelvin et al. $\sim$0.33 arcsec and root-mean-square difference $R_e$,this work - $R_e$,Kelvin et al. $\sim$0.18 arcsec). Table 4.2 shows the final $R_e$ for each galaxy.

4.3.2 Stellar mass

Taylor et al. (2011) presented the stellar masses for galaxies in the GAMA survey derived from spectral energy distribution (SED) fitting using a Chabrier (2003) IMF. They show that these stellar masses can be approximated using the $g$- and $i$-band rest-frame colours. In this work I use the $(g - i)$ relationship derived in Taylor et al. (2011) to calculate the stellar masses of the Jimmy et al. (2013) sample, the BCGs in the clusters Virgo, Coma, Abell 85, 168 and 2399, and the observed galaxies.

For the 7 galaxies selected from the GAMA survey, I use the photometry presented in Taylor et al. (2011) which has been shown to be consistent with the SDSS Petrosian photometry. For the 15 galaxies selected from the SDSS (10 in Jimmy et al. 2013, 5 in the observed sample), and the BCGs in the Virgo, Coma, Abell 85, 168 and 2399 clusters, I obtain the Petrosian magnitudes from the NYU Value-Added Galaxy Catalog (Blanton et al. 2005), specifically the k-corrected rest-frame values.$^4$ (Blanton & Roweis 2007). The galaxies C4 2048 (from this sample) and C4 1027 (from Jimmy et al. 2013), do not have

$kcorrect/kcorrect.nearest.model.z0.00.fits; http://cosmo.nyu.edu/blanton/vagc/kcorrect.html$
spectroscopic data in the SDSS. I use the \( z \) measured in these observations (Section 4.3.4) to calculate the Petrosian absolute magnitudes and their stellar masses. The final stellar masses come from the following equation:

\[
\log(M_*/M_\odot) = 1.15 + 0.70(g - i) - 0.4M_i
\]

where \( M_i \) is the absolute AB \( i \) magnitude (eq 8 from Taylor et al., 2011). The average 1\( \sigma \) statistical uncertainties on \( M_* \) derived from this equation (see Taylor et al., 2011) are 0.1 dex. The BCGs in the Fornax and Abell 1689 cluster do not have Petrosian flux measurements in the SDSS. Therefore, I calculate their stellar mass from the \( k \)-band magnitudes published in Scott et al. (2014) and D’Eugenio et al. (2012) respectively. Table 4.2 lists the stellar masses of all the BCGs in the sample.

### 4.3.3 Properties of groups and clusters

The sample is composed of BCGs residing in a wide range of halo masses. To study the environmental effects on the angular momentum of these galaxies I use two properties of the cluster that describe their evolutionary stages: cluster mass and dominance. I now describe these properties and how they were measured.

#### Halo mass

I calculate the virial mass (\( M_{200} \)) of the groups and clusters, using the velocity dispersion (\( \sigma_{cl} \)) from GAMA (Robotham et al., 2011), the C4 catalogue (Miller et al., 2005; von der Linden et al., 2007) and those found in the literature (Drinkwater et al., 2001; Halkola et al., 2006; Kubo et al., 2007; Fogarty et al., 2014). \( M_{200} \) is the mass contained within \( R_{200} \) which is the radius at which the density is 200 times the universal critical density (e.g. White, 2001). I use the following equation to calculate \( M_{200} \) (e.g. Finn et al., 2005; von der Linden et al., 2007; Koyama et al., 2010):

\[
M_{200} = 1.71 \times 10^{15} \left( \frac{\sigma_{cl}}{1000 \text{ km s}^{-1}} \right)^3 \frac{1}{\sqrt{\Omega_\Lambda + \Omega_0(1+z)^3}} M_\odot
\]

where \( \sigma_{cl} \) is the velocity dispersion of the cluster. The errors are propagated from \( \sigma_{cl} \). The \( M_{200} \) for each group and cluster in our sample are listed in Table 4.2.
Dominance

The clusters from [Jimmy et al. (2013)] and the groups and clusters from the new SPIRAL sample do not have X-ray observations, therefore, to track the cluster/group merging status I rely on dominance measurements. The dominance is the magnitude gap ($\Delta m_{1,2}$) between the brightest galaxy in the cluster (BCG) and the second brightest. This measurement has been found to be a good indicator of recent cluster mergers (Tremaine & Richstone 1977b; Loh & Strauss 2006; Smith et al. 2010). Statistically, large magnitude gaps are common in halos that have not undergone recent halo-halo mergers. These clusters are homogeneous with strong cool cores, and only a low percentage of the cluster mass resides in cluster substructure ($\sim 3$ percent; Smith et al. 2010). Small magnitude gaps likely indicate a young unrelaxed group and/or a recent cluster merger. These clusters are more heterogeneous with large fractions of substructure ($\sim 30$ percent of the cluster mass; Smith et al. 2010; Dariush et al. 2010; Coenda et al. 2012; Martel et al. 2014).

For the 7 galaxies selected from GAMA, the dominance values are presented in the G3C (Robotham et al. 2011). To calculate the dominance they used the SDSS apparent $r$-band Petrosian magnitudes. For the 14 clusters (9 from [Jimmy et al. 2013] 5 from our observations) selected from the SDSS the dominance was calculated from the $r$-band Petrosian magnitudes. For Virgo, Fornax, Coma, Abell 1689, 85, 168 and 2399 clusters I use the $r$-band magnitudes found in the literature (Cappellari et al. 2011; D’Eugenio et al. 2012; Houghton et al. 2013; Scott et al. 2014; Fogarty et al. 2015).

4.3.4 Spectroscopic measurements: stellar kinematics

The stellar kinematics are the key component of this analysis. In order to ensure a reliable measurement of the stellar kinematic parameters of our new SPIRAL observations: line-of-sight velocity dispersion ($\sigma$) and stellar velocity ($V$), it is necessary to optimise the signal-to-noise (SN) and spatial resolution of the observation. To do so, I use the Voronoi binning method of Cappellari & Copin (2003) which performs a SN cut across all the spaxels (i.e. removes all spaxels with SN below the cut), to later bin the remaining spaxels to reach the minimum SN required. I run Markov Chain Monte Carlo (MCMC) simulations to choose the optimal SN cut and SN required. I find that the optimal SN cut for our data is 3 and the optimal SN after binning is 10. This leaves us with a spatial coverage of 0.3 to 1 $R_e$ depending on the redshift at which the galaxy was observed.

I measure the stellar kinematics of each binned spaxel with the penalized-PiXel Fitting
4.3. Analysis

code (PPXF; Cappellari & Emsellem, 2004). PPXF fits the observed spectroscopic data to a library of stellar spectra. In this analysis I use the Medium-resolution Isaac Newton Telescope library of empirical spectra (MILES; Sánchez-Blázquez et al., 2006b), particularly the G6 to M1 templates of stars (as in Jimmy et al., 2013). The resolution of the observed spectra (FWHM = 2.7 Å) is similar to the resolution of the MILES templates (FWHM = 2.5 Å). PPXF convolves the library spectra to the FWHM of the galaxy spectra. To correct for the systemic velocity I use the Vsys flag provided by PPXF.

Our wavelength coverage spans from 3800 to 5600 Å. The fitting region varies from one galaxy to another, depending on the redshift of the galaxy and the information lost due to bad pixels. For 10 out of 12 of the galaxies I was able to fit strong absorption-line features such as Ca\textsubscript{K}+H\lambda3933, 3968, G-band\lambda4307, H\beta, and/or Mg-b\lambda5175 (Figure 4.3). For the remaining two galaxies I had to rely on the weaker features H\delta, H\gamma, Fe\lambda5015, Fe\lambda5270 and Fe\lambda5335.

To calculate the uncertainties in the measured velocities and velocity dispersions I use 100 MCMC iterations. In each iteration I add random noise of the order of the residuals from the first fit, to the best fit spectrum. The total galaxy velocity dispersion is calculated by stacking all the spaxels within 1 \( R_e \) (or the largest radius I reach) and running PPXF on the final spectrum. The final redshifts and velocity dispersions can be found in Table 4.2. The kinematic maps are in Figure 4.5.

4.3.5 Specific Angular momentum

The SAURON (de Zeeuw et al., 2002) and ATLAS\textsuperscript{3D} (Cappellari et al., 2011) surveys introduced a new method to quantify the rotation in galaxies. This method is based on the parameter \( \lambda_R \) which is a proxy of the specific angular momentum, and the ellipticity parameter (\( \varepsilon \)). \( \lambda_R \) (Emsellem et al., 2007) is calculated using the stellar velocity (\( V \)) and line-of-sight velocity dispersion (\( \sigma \)) as a function of radius \( R \) as follows:

\[
\lambda_R \sim \frac{\langle R|V| \rangle}{\langle R\sqrt{V^2 + \sigma^2} \rangle}
\] (4.3)

The ellipticity parameter, \( \varepsilon \), is calculated using the IDL routine find_galaxy.pro publicly available in the mge_fit_sectors package\footnote{http://www-astro.physics.ox.ac.uk/~mxc/idl/}. This uses the IFS data over an aperture defined by the SN cut (\( \sim 0.5 \ R_e \)). With these two parameters I can classify the galaxies as fast
rotators (FR) and slow rotators (SR). A galaxy is defined as fast-rotating if:

$$\lambda_{R_e/2} > (0.265 \pm 0.01) \times \sqrt{e_{R_e/2}}$$  \hspace{1cm} (4.4)$$

where $\lambda_{R_e/2}$ and $e_{R_e/2}$ are the specific angular momentum and the ellipticity measured within 0.5 $R_e$ (Emsellem et al. 2011). I pick 0.5 $R_e$ as the standard aperture since most of the objects in Jimmy et al. (2013) and the new SPIRAL observations do not extend to 1 $R_e$. In the 2 cases where the galaxy does not reach 0.5 $R_e$ (C4 2074 and C4 2055) I use the $\lambda_R$ at the maximum radius ($\sim 0.3 R_e$) Emsellem et al. (2011) and Arnold et al. (2014) showed that despite the variations in the $\lambda_R$ profiles after 0.5 $R_e$, the classification of the fast and slow rotators from 0.5 $R_e$ holds to larger radii in the majority of cases.

To test if the $\lambda_{R_e/2}$ measured from the new SPIRAL observations are directly comparable with the $\lambda_{R_e/2}$ of other BCGs in the literature, I use the galaxies in Jimmy et al. (2013), which were observed with the VIMOS spectrograph and have higher SN. These galaxies are degraded to SPIRAL quality by adding noise to the VIMOS reduced data cubes and running MCMC simulations. I find that the noisier observations overestimate the $\lambda_{R_e/2}$ measurements by 0.05 $\pm$ 0.02. Therefore, I subtract 0.05 from the $\lambda_{R_e/2}$ from the SPIRAL observations. This ensures that the new observations are directly comparable
with other BCGs in the literature. The uncertainties in $\lambda_{Re/2}$ are propagated using Taylor series expansions from the errors on the $V$ and $\sigma$ measurements.

The new SPIRAL galaxies cover a wide range in redshifts $0 < z \leq 0.2$. Therefore, there are variations in the spatial resolution with redshift. I have tested the influence of these variations on the measurement of $\lambda_{Re/2}$ by lowering the resolution of the lowest $z$ galaxies in a way that would be comparable to observing them at $z = 0.2$. I find that by decreasing the spatial resolution, the $\lambda_{Re/2}$ parameter increases by 5 percent (i.e. the galaxies are skewed to fast rotation). This does not affect the overall result since the effect falls within the measured uncertainty.

**Kinematic classification of BCGs**

The final kinematic classification of the galaxies in our sample is based on the empirical relation between $\lambda_{Re/2}$ and $\varepsilon_{Re/2}$ (right-hand panel of Figure 4.4). The $\lambda_R$ profiles for the newly observed BCGs and the galaxies in Jimmy et al. (2013) are shown in the left-hand panel of Figure 4.4. As the error bars from the $\lambda_{Re/2}$ measurements are large there is a probability that a true slow rotator may sit above the $\lambda_{Re/2}$ and $\varepsilon_{Re/2}$ empirical relation. Therefore, I assign a probability equal to the fraction of the error bar above or below the relation in Eq 4.4. The galaxies in the SPIRAL sample are classified as fast or slow rotator candidates according to their probabilities.

I maintain the classifications made for the other galaxies in the literature (Emsellem et al., 2011; D’Eugenio et al., 2012; Jimmy et al., 2013; Houghton et al., 2013; Scott et al., 2014; Fogarty et al., 2014; Fogarty et al., 2015) and I list the probability of that galaxy classification as per its error bars. The BCGs in Abell 1689 and Coma have already been assigned a probability by D’Eugenio et al. (2012) and Houghton et al. (2013) respectively. In Table 4.3 I show the $z$, $\lambda_{Re/2}$, $\varepsilon_{Re/2}$, and the probability of being a slow rotator for each galaxy.

## 4.4 Results

I find that 65 ± 8 percent of the newly observed sample are fast rotator candidates. This percentage is higher than that found by previous studies and could suggest environmental dependency given the low stellar and halo masses covered by these observations. The following sections summarise the final results and analyse whether fast or slow rotation in
Chapter 4. Angular momentum of BGG/BCGs

Figure 4.4: Kinematic classification of BCGs. Fast rotators are shown as blue circles and slow rotators as red squares. **Left-hand panel:** Proxy for specific angular momentum ($\lambda_R$) vs radius. The dashed and solid lines represent the 12 BCGs observed here. The dotted and dot-dashed lines are the BCGs from Jimmy et al. (2013). The fast rotators have higher values of $\lambda_R$ and generally increasing profiles with increasing radius. The vertical dotted line shows the fiducial radius of 0.5 $R_e$. **Right-hand panel:** The proxy for specific angular momentum and ellipticity at 0.5 $R_e$ ($\lambda_{R_e/2}$, $\varepsilon_{R_e/2}$). The symbols represent: the observed BCGs (filled), the BCGs from Jimmy et al. (2013, open), and the BCGs from Virgo, Fornax, Coma, Abell 1689, 85, 168 and 2399 (crossed). The errors are the uncertainties derived from the velocity measurements (standard deviation of 100 MCMC). The black dots are the simulated BCGs from Martizzi et al. (2014). The black solid line is the empirical division between fast and slow rotators. I find a probability of 65 ± 8 that the newly observed galaxies are fast rotator candidates, and an overall probability of 41 ± 3 percent across the whole sample of 29 BCGs.

BCGs is connected to galaxy size and stellar mass, or environment. These analyses include the new observations presented here (12 BCGs), the BCGs from Jimmy et al. (2013) and the BCGs in the Virgo, Fornax, Coma, Abell 1689, 85, 168 and 2399 clusters. Once all BCGs are included, I find that 41 ± 3 percent of the galaxies are likely to be fast rotators.

4.4.1 Angular momentum of BCGs as a function of stellar mass

The angular momentum of galaxies has been shown to be correlated with stellar mass. Due to their high stellar masses and large sizes, BCGs are expected to be slow rotators. Cappellari et al. (2013b) and Cappellari (2013c) have shown that above log($M_*/M_\odot$) ~ 11.3 they observe mostly slow-rotating early-type galaxies. They define this as a critical mass...
4.4. Results

(M_{*\text{crit}}). However, their sample only includes the BCGs in the Virgo and Coma clusters and so this M_{*\text{crit}} may not hold for the whole population of BCGs.

The lower panel of Figure 4.6 shows $\lambda_{R_e/2}$ as a function of stellar mass. Galaxy rotation decreases with stellar mass. The upper panel of Figure 4.6 shows the distribution of M_* for fast and slow rotator candidates. The mean stellar mass in fast rotators ($\log(M_*/M_\odot) = 11.17 \pm 0.06$, the uncertainty is the error on the mean) is a factor of 1.5 smaller than the mean stellar mass in slow rotators ($\log(M_*/M_\odot) = 11.33 \pm 0.09$). I observe slow rotator candidates across the whole stellar mass range (log(M_*/M_\odot) = 10 to log(M_*/M_\odot) = 12). Above the Cappellari (2013c) critical mass slow rotator candidates dominate over fast rotators (6/9 ± 0.1 BCGs), and there are no fast-rotating BCG candidates above $\log(M_*/M_\odot) \sim 11.54$. The angular momentum of the BCGs in our sample show the same dependence on stellar mass as the early-type galaxies from ATLAS3D. The mean stellar masses for fast and slow rotators are summarised in Table 4.4.

4.4.2 Angular momentum of BCGs as a function of size

Figure 4.7 shows the proxy for angular momentum as a function of radius. The data suggest an anti-correlation between $\lambda_{R_e/2}$ and $R_e$ (Pearson coefficient of -0.29 with a probability of 99.89). In general, slow-rotating BCG candidates have larger $R_e$ ($R_e = 10.4 \pm 1.1$ kpc) and fast-rotating BCG candidates have smaller $R_e$ ($R_e = 7.7 \pm 1.1$ kpc). I begin to observe slow rotators from $R_e \sim 4$ kpc. The mean radii for fast and slow rotators are summarised in Table 4.4.

4.4.3 Angular momentum of BCGs as a function of halo mass

Due to the small number of BCG IFS observations to date, it is not yet known whether BCG stellar kinematics are influenced by the mass of their host halo. I present here the first analysis of the effect of environment on the angular momentum of BCGs, including a representative range of group and cluster halo masses (12 < log(M_{200}/M_\odot) < 15.5).

The lower panel of Figure 4.8 shows the $\lambda_{R_e/2}$ of BCGs as a function of their host halo mass. Slow-rotating candidates, on average, reside in clusters a factor of two more massive ($\log(M_{200}/M_\odot) = 14.46 \pm 0.18$) than fast-rotating candidates ($\log(M_{200}/M_\odot) = 14.17 \pm 0.14$). The upper panel of Figure 4.8 shows the halo mass distribution for slow and fast-rotating BCG candidates. The fraction of slow rotators increases with increasing halo mass and above $\log(M_{200}/M_\odot) \sim 15$, I only observe slow rotator candidates. This
Chapter 4. Angular momentum of BGG/BCGs

explains why the new observations of 12 BCGs (mostly residing in group halos) have a higher fraction of fast rotators ($0.65 \pm 0.08$) than the fraction seen in previous studies ($0.3;\ Jimmy\ et\ al.,\ 2013$). The mean cluster halo masses for fast and slow rotator candidates are summarised in Table 4.4.

The simulations of Martizzi et al. (2014) mainly consist of clusters ($\log(M_{200}/M_\odot) > 13.8$). Comparing the 16 observed clusters in the same mass range with their simulations, I find that the mean specific angular momentum measured here ($\lambda_{R_e/2} = 0.15 \pm 0.02$) is consistent with theirs ($\lambda_{R_e/2} = 0.05 \pm 0.09$) within $2\sigma$ although the distributions are different. The observed probability of slow rotators ($\sim 0.7$) is also consistent with their simulations.

4.4.4 Angular momentum of BCGs as a function of the cluster status

Dominance is a good indicator of the cluster/group merging status. Small magnitude gaps ($\Delta m_{1,2} < 1.0$) are likely to indicate a recent halo merger. This is supported by the percentage of the mass of these clusters residing in cluster substructure ($\geq 10$ percent; Smith et al., 2010).

Figure 4.9 shows that BCGs residing in clusters with high dominance ($\Delta m_{1,2} > 1.5, \sim 3$ percent of cluster mass is in substructure) are all slow rotator candidates. This suggests that the merging status of the host halo could be influencing the BCG angular momentum. The mean dominance values of the host of fast and slow rotator candidates are summarised in Table 4.4.
4.5 Discussion

This Chapter has presented the angular momentum of BCGs from IFS observations. I include new observations of 12 BCGs observed with SPIRAL on the Anglo-Australian Telescope at redshifts $0 < z < 0.2$. These galaxies, together with the 10 BCGs presented in [Jimmy et al. (2013)], and the BCGs in the Virgo, Fornax, Coma, Abell 1689, 85, 168 and 2399 clusters, span a wide range of halo masses, $12 < \log(M_{200}/M_\odot) < 15.5$, as well as a wide range of stellar masses, $10 < \log(M_*/M_\odot) < 11.8$. The composite sample presented here is not complete, however, it is representative of a wide range of environments. This is the first analysis of the role of stellar mass and environment on the stellar kinematics of BCGs using IFS. In the following Section I discuss our results and compare them with previous work.

4.5.1 The dependence of BCG angular momentum on stellar mass and environment

Galaxy evolution is not an isolated phenomena, the way galaxies grow and transform depends on many variables acting together. Here I analyse the BCGs, putting their angular momentum in context with their stellar mass and environment.

The size and mass of galaxies are known to be correlated (e.g. [Bernardi et al. 2007, Bernardi 2009, Laporte et al. 2013, Kravtsov 2013, Kravtsov et al. 2014, Vulcani et al. 2014]), such that more massive galaxies have larger radii. Cappellari et al. (2013b) explored the dependence of angular momentum on the size – stellar mass relationship of early-type galaxies in the ATLAS$^3D$ sample, finding that these galaxies evolve from small, less massive, fast rotators to larger, massive, slow rotators.

Figure 4.10 shows the size – stellar mass relationship for the BCGs in our sample. Our results agree with the predictions made by the ATLAS$^3D$ team (Emsellem et al. 2011, Cappellari et al. 2013b, Naab et al. 2014). I confirm that the majority of galaxies in our sample above Cappellari (2013c)’s critical stellar mass $\log(M_{*,\text{crit}}/M_\odot) = 11.3$ ($6/9 \pm 0.1$ BCGs) are slow rotator candidates. Similar to the general early-type galaxy population, the BCG angular momentum appears to evolve with the size – stellar mass relationship.

Halo mass has been predicted to be an important factor in the stellar mass growth of BCGs (White & Rees 1978, Khochfar & Burkert 2003, De Lucia & Blaizot 2007, Oser...
et al., 2010; De Lucia et al., 2012). It is also well known that stellar mass is correlated with host cluster halo mass, such that bigger halos tend to host more massive BCGs (Aragon-Salamanca et al., 1998; Brough et al., 2008; Stott et al., 2008, 2010; Lidman et al., 2012; Stott et al., 2012; Burke & Collins, 2013; Lin et al., 2013; Lidman et al., 2013; Shankar et al., 2014; Inagaki et al., 2014; Oliva-Altamirano et al., 2014; Luparello et al., 2015; Zhang et al., 2015; Shankar et al., 2015). Figure 4.11 shows the $M_\star - M_{200}$ relationship for the galaxies of our sample, exploring the connection between this relationship and the fast or slow rotation of the galaxy.

From Figure 4.11 I see that BCG angular momentum appears to be influenced not only by the galaxy stellar mass, but also by its host cluster mass. The most massive BCGs ($\log(M_\star/M_\odot) > 11.54$) in our sample, hosted by the most massive halos ($\log(M_{200}/M_\odot) > 15$) are all slow rotators. This suggests that the angular momentum of BCGs is linked to their evolution through the $M_\star - M_{200}$ relationship. However, while I see slow rotator candidates across the whole stellar mass and halo mass range, I observe that the majority of fast rotator candidates reside, on average, in less massive halos and have lower stellar masses compared to the slow rotator candidates.

I also explore the cluster merging status by analysing the dependence of the BCG angular momentum on cluster dominance. I find that clusters with large dominance ($\Delta m_{1,2} > 1.5$) only host slow-rotating BCG candidates. These clusters are expected to be homogeneous with low fractions of substructure ($\sim 3$ percent of cluster mass; Dariush et al., 2010; Smith et al., 2010).

There are some clusters in our sample such as the Virgo and Fornax clusters, which have small magnitude gaps. However, they are in a relaxed state. We can see that most fast rotators are in clusters with dominance $\Delta m_{1,2} < 1.5$ and most of slow rotators have dominance greater than 0.5. The exceptions to this rule are the Virgo and Fornax clusters which have slow rotator BCGs and low dominance ($\Delta m_{1,2},$ Virgo = 0.37, $\Delta m_{1,2},$ Fornax = 0.4).

These results suggest that while BCG angular momentum is influenced by their cluster, there are other influences present too. Cluster dominance could also be linked to a local effect, as the two brightest galaxies in a cluster could be sharing the same substructure. This would mean the dominance was tracing a galaxy-scale effect rather than a
4.5. Discussion

Looking at our sample Abell 2399 (Fogarty et al., 2014; X-ray and optical observations) has 3 brightest galaxies all of which are fast rotators. Two of them are sharing the same substructure and have a difference in magnitude less than 0.07. Therefore, the hypothesis of low cluster dominance due to a local effect becomes true. However, the brightest of the galaxies in Abell 2399 sits in a different substructure with no other massive galaxies nearby that could affect its angular momentum. In this case the fast rotation is likely to be due to the state of the cluster rather than local interactions. Abell 168 (Fogarty et al., 2014; X-ray and optical observations) has two BCGs, one of them is a slow rotator and the other one is a fast rotator. These galaxies sit in different substructures. Therefore, the fast rotation is unlikely to be the result of a local interaction.

The cluster status (relaxed or unrelaxed) would affect the accretion of mass in BCGs. Cluster-cluster mergers could trigger new star formation and change the BCG spin and orientation which would enhance probability of merging (see Martel et al. 2014). Unrelaxed clusters, will show gas rich major mergers and violent shocks that could increase the angular momentum in BCGs. A relaxed cluster, on the contrary, tends to have a well established BCG sitting at the centre of the potential well, susceptible to minor mergers. These clusters are gas depleted which causes an spin-down in the central galaxy. Minor mergers are not powerful enough to change the spin in BCG therefore they generate dispersion dominated galaxies (slow rotators, Naab et al., 2014).

BCGs represent a challenge for cosmological simulations. Martizzi et al. (2014) have shown the difficulties of modelling such complex galaxies. Their massive halos require bigger cosmological boxes than those currently available, and the implementation of many physical processes acting together at a given time. The implementation of AGN feedback has brought simulated galaxies into closer agreement with observations. However, to probe the influence of cluster evolution on the angular momentum of BCGs, new simulations encompassing the group-cluster mass range are needed.

In summary, I have shown the first indication of a dependance of BCG angular momentum on the $M_* - M_{200}$ relationship. From this I infer that BCG angular momentum evolves as the BCG increases in stellar mass and its host halo increases in mass. The connection with cluster dominance suggests that the angular momentum can also be affected by re-
Chapter 4. Angular momentum of BGG/BCGs

Cent cluster-cluster mergers. However, larger samples and more detailed simulations are needed to confirm our results.

4.6 Conclusions

I have presented the role of environment on the angular momentum of 29 BCGs from a composite sample of new (12 BCGs) and previous IFS observations (17 BCGs). The sample spans a cluster halo mass range of $12 < \log(M_{200}/M_\odot) < 15.5$. Our results suggest:

1) A connection between the BCG angular momentum and the stellar mass – halo mass relationship, as well as, the cluster evolutionary status (whether if it is an homogeneous cluster or not).

2) I do not find fast-rotating BCG candidates with stellar mass $\log(M_*/M_\odot) > 11.54$, hosted by clusters of mass $\log(M_{200}/M_\odot) > 15$, or dominance $\Delta m_{1,2} > 1.5$.

3) While BCG angular momentum appears to depend on galaxy radius and stellar mass, similar to the general population of early-type galaxies, BCG angular momentum also depends on environment as described by host halo mass and dominance.

A larger, statistically significant sample, is needed to further probe these results. The next generation of IFS surveys will bring significantly increased sample sizes: MASSIVE (Ma et al., 2014), MaNGA (Bundy et al., 2014), SAMI (Bryant et al., 2015), HECTOR (Bland-Hawthorn, 2015); offering the chance to confirm the findings presented here.
Table 4.2: Galaxy and halo properties. The top section are the new SPIRAL observations. The middle section contains the galaxies from Jimmy et al. (2013). The bottom section shows other galaxies in the literature. The galaxies are sorted by decreasing halo mass. The references from where the properties were taken are shown below. (1) Galaxy ID. (2) Group or Cluster ID. (3) Redshift of the galaxy. (4) Effective radius in kpc. (5) Stellar mass. (6) Cluster viral mass from the velocity dispersions found in the literature. (7) Halo dominance derived from the r-band magnitudes.

| Galaxy | Group/
Cluster ID | z  | R_e [kpc] | log M_* [M_☉] | log M_200 [M_☉] | m_{1,2} |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>G 559552a</td>
<td>200051a</td>
<td>0.136</td>
<td>3.04a</td>
<td>11.17a</td>
<td>14.50a</td>
<td>0.02a</td>
</tr>
<tr>
<td>G 144764a</td>
<td>200020a</td>
<td>0.173</td>
<td>3.81a</td>
<td>11.49a</td>
<td>14.26a</td>
<td>1.13a</td>
</tr>
<tr>
<td>C4 2048b</td>
<td>2048b</td>
<td>0.094</td>
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<td>1.39b</td>
</tr>
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<td>G 22992a</td>
<td>200046b</td>
<td>0.200</td>
<td>3.14a</td>
<td>11.53a</td>
<td>14.23b</td>
<td>1.14b</td>
</tr>
<tr>
<td>G 509077a</td>
<td>30243a</td>
<td>0.136</td>
<td>2.09d</td>
<td>10.91d</td>
<td>14.19b</td>
<td>0.16b</td>
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<tr>
<td>C4 2121b</td>
<td>2121b</td>
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<td>5.07c</td>
<td>10.91c</td>
<td>14.15b</td>
<td>1.07b</td>
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<tr>
<td>G 62501a</td>
<td>30050a</td>
<td>0.138</td>
<td>3.76a</td>
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<tr>
<td>G 535178a</td>
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<tr>
<td>C4 2216b</td>
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<td>11.01f</td>
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<tr>
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<td>13.71b</td>
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</tr>
<tr>
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<td>1.09b</td>
</tr>
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</tr>
<tr>
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<td>0.050f</td>
<td>2.72</td>
<td>10.91f</td>
<td>13.63b</td>
<td>1.33b</td>
</tr>
</tbody>
</table>

12^d Abell 1689 0.183^d 42.96^d 11.86^d 15.50^d 0.91^d
NGC 4889 Coma 0.022 16.88^g 11.30^c 15.27^b 0.22^s
019^c Abell 85 0.055^c 17.45^c 11.62^c 15.07^c 1.18^c
086^c Abell 2399 0.058^c 6.04^c 10.96^c 14.72^c 0.67^c
M49 Virgo 0.003 6.10^i 11.77 14.62 0.37^i
042^c Abell 168 0.045^c 12.17^c 11.32^c 14.38^c 0.94^c
NGC 1399 Fornax 0.005 4.24^b 11.64^b 13.94^b 0.4^b
Table 4.3: The galaxies are sorted by halo mass (see Table 4.2). Column 3 and 4 show the proxy for the specific angular momentum and ellipticity (see Section 3.5). Column 5 shows the probability of the galaxy to be a slow rotator candidate.

Note: All galaxies with $P(SR) > 40$ are classified as slow rotator candidates.

$^a$The fiducial radius of these BCGs is $1R_e$.

$^b$The fiducial radius of these BCGs is less than $0.3R_e$.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>$z$</th>
<th>$\lambda_{R_e/2}$ $\pm 0.07$ at $z &lt; 0.07$</th>
<th>$\varepsilon_{R_e/2}$ $\pm 0.01$</th>
<th>$P(SR)$ $%$</th>
</tr>
</thead>
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<td>0.270</td>
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</tr>
<tr>
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<td>0.242</td>
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<td>0</td>
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<tr>
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<td>0.149</td>
<td>0.078</td>
<td>0</td>
</tr>
<tr>
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<td>0.073</td>
<td>0.094</td>
<td>55</td>
</tr>
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<tr>
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<td>0.096</td>
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<td>0.106</td>
<td>0.082</td>
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<td>0.080</td>
<td>50</td>
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<td>0.256</td>
<td>0</td>
</tr>
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<td>1050</td>
<td>0.072</td>
<td>0.061</td>
<td>0.140</td>
<td>75</td>
</tr>
<tr>
<td>2039</td>
<td>0.083</td>
<td>0.090</td>
<td>0.060</td>
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<td>0.149</td>
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<td>0.240</td>
<td>100</td>
</tr>
<tr>
<td>086</td>
<td>0.058</td>
<td>0.256$^a$</td>
<td>0.449</td>
<td>0</td>
</tr>
<tr>
<td>M49</td>
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<td>0.019</td>
<td>0.070</td>
<td>100</td>
</tr>
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<td>0.045</td>
<td>0.043</td>
<td>0.100</td>
<td>100</td>
</tr>
<tr>
<td>NCG 1399</td>
<td>0.005</td>
<td>0.080$^a$</td>
<td>0.090</td>
<td>52</td>
</tr>
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Figure 4.5: Kinematic maps of the new SPIRAL observations. $V$ is shown in the upper panels. $\sigma$ is shown in the bottom panels. Each galaxy has its number ID at the bottom-left corner of panel and its classification as fast or slow rotator candidate at the upper-right corner. The orientation of the galaxy is shown at the bottom-right corner. The dashed line represents the photometric position angle measured by galfit.
Chapter 4. Angular momentum of BGG/BCGs

Figure 4.6: Proxy for specific angular momentum as a function of stellar mass. The fast rotator candidates are shown as blue circles and slow rotator candidates are shown as red squares. At the top of the lower panel representative measurement uncertainties are shown. The errors in $\lambda_{R_e/2}$ are derived from the uncertainties on the velocity and velocity dispersion measurements. The errors in $M_*$ were calculated in Taylor et al. (2011). The lower panel shows the observed BCGs (filled symbols), the BCGs from Virgo, Coma, Fornax, Abell 1689, 85, 168 and 2399 (crossed symbols), and the BCGs from Jimmy et al. (2013, open symbols). The upper panel shows the stellar mass distribution of fast rotator and slow rotator candidates. The dashed line (fast rotators), dot-dashed line (slow rotators) and black symbols (reflected in the lower panel) represent the mean stellar masses. Their error bars are the standard errors on the mean. The dotted line represents the critical mass from Cappellari (2013c). The slow rotator candidates on average have higher stellar mass than fast rotator candidates. The red arrow represents the stellar mass ($\log(M_*/M_\odot) \sim 11.54$) above which all BCGs in our sample are slow rotator candidates.
Figure 4.7: Proxy for specific angular momentum as a function of effective radius. The fast rotator candidates are shown as blue circles and slow rotator candidates are shown as red squares. At the top of the lower panel representative measurement uncertainties in $\lambda_{R_e/2}$ are shown. They are derived from the uncertainties on the velocity and velocity dispersion measurements. The lower panel shows the observed BCGs (filled symbols), the BCGs from Virgo, Coma, Abell 1689, 85, 168 and 2399 (crossed symbols), and the BCGs from Jimmy et al. (2013, open symbols). The upper panel shows the $R_e$ distribution of fast rotator and slow rotator candidates. The dashed line (fast rotators), dot-dashed line (slow rotators) and black symbols represent (reflected in the lower panel) the mean radii. Their error bars are the standard errors on the mean. The data suggest an anti-correlation between $\lambda_{R_e/2}$ and $R_e$ (99. percent probability 99.89).

Table 4.4: Mean parameters for fast (FR) and slow-rotating (SR) candidates.

<table>
<thead>
<tr>
<th></th>
<th>FR mean</th>
<th>error on the mean</th>
<th>SR mean</th>
<th>error on the mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{R_e/2}$</td>
<td>0.233</td>
<td>0.022</td>
<td>0.066</td>
<td>0.007</td>
</tr>
<tr>
<td>$\log(M_*/M_\odot)$</td>
<td>11.17</td>
<td>0.059</td>
<td>11.33</td>
<td>0.09</td>
</tr>
<tr>
<td>$R_e$(kpc)</td>
<td>07.72</td>
<td>1.1</td>
<td>10.44</td>
<td>1.1</td>
</tr>
<tr>
<td>$\log(M_{200}/M_\odot)$</td>
<td>14.17</td>
<td>0.14</td>
<td>14.46</td>
<td>0.18</td>
</tr>
<tr>
<td>$\Delta m_{1.2}$</td>
<td>0.77</td>
<td>0.14</td>
<td>1.22</td>
<td>0.15</td>
</tr>
</tbody>
</table>
Figure 4.8: Proxy for specific angular momentum as a function of cluster halo mass. Fast rotator candidates are shown as blue circles and slow rotator candidates are shown as red squares. The filled symbols are the new SPIRAL observations, the crossed symbols represent the BCGs from Virgo, Fornax, Coma, Abell 1689, 85, 168 and 2399, and the open symbols are the BCGs from Jimmy et al. (2013). At the top of the lower panel representative measurement uncertainties are shown. The errors in $\lambda_{R_e/2}$ and $M_{200}$ are derived from the uncertainties on the velocity and velocity dispersion measurements. The simulations of Martizzi et al. (2014) are shown as black dots. The upper panel shows the halo mass distribution of slow and fast rotator candidates. The dashed line (fast rotators), dot-dashed line (slow rotators) and black symbols (reflected in the lower panel) represent the mean halo masses. The errors are standard errors on the mean. The results suggest that fast rotators are more likely to be found in group environments. There are no fast-rotating BCGs in halos with mass $M_{200} (M_\odot) > 15$ (red arrow).
4.6. Conclusions

Figure 4.9: Proxy for specific angular momentum as a function of cluster dominance. The galaxies are colour-coded with fast rotator candidates as blue circles and slow rotator candidates as red squares. Average error bars are illustrated at the top of the bottom panel. The newly observed BCGs are the filled symbols, the BCGs from Jimmy et al. (2013) are the open symbols, and the BCGs from other clusters in the literature are the crossed symbols. At the top of the lower panel representative measurement uncertainties in $\lambda_{R_e/2}$ are shown. They are derived from the uncertainties on the velocity and velocity dispersion measurements. The upper panel shows the dominance distribution for the clusters hosting fast rotator candidates (blue bars; dashed line) and slow rotator candidates (open red bars; dot-dashed line). The black symbols in the lower panel represent the mean values for slow and fast rotators. The errors are the standard errors on the mean. The likely percentages of expected cluster mass residing in cluster substructure at a given dominance, are indicated at the bottom of the panel (Smith et al. 2010). The red arrow shows the dominance ($\Delta m_{1.2} \sim 1.5$) above which I do not observe fast rotator candidates.
Figure 4.10: Proxy of specific angular momentum dependency on the size – stellar mass relationship in BCGs. The fast rotator candidates are shown as blue circles and slow rotator candidates are shown as red squares. The representative error bar is at the top of the panel. The errors in $M_*$ were calculated in Taylor et al. (2011). The filled symbols represent the new observations of 12 BCGs, the crossed symbols represent the BCGs from Virgo, Coma, Fornax, Abell 1689, 85, 168 and 2399, and the open symbols are the BCGs from Jimmy et al. (2013). The mean values are shown in black. The errors are the errors on the mean. The dotted line represents the critical stellar mass from Cappellari (2013c). The red arrow represents the stellar mass cut-off above which I do not observe fast rotator candidates. Our results suggest a connection between the BCG angular momentum and the size – stellar mass relationship. Fast rotators have small radii and low masses, while slow rotators have larger radii and higher stellar masses.
Figure 4.11: The stellar mass – halo mass relationship and its connection with the specific angular momentum. The fast rotator candidates are shown as blue circles and the slow rotator candidates are shown as red squares. The errors in $M_*$ were calculated in Taylor et al. (2011) and the errors in $M_{200}$ are derived from the uncertainties in the velocity and velocity dispersion measurements (left-lower corner of the panel). The filled symbols are the new observations of BCGs, the crossed symbols represent the BCGs from Virgo, Coma, Fornax, Abell 1689, 85, 168 and 2399, and the open symbols are the BCGs from Jimmy et al. (2013). The mean values are shown in black. The errors are the errors on the mean. The dotted line represents the critical stellar mass from Cappellari (2013c). All galaxies above $\log(M_*/M_\odot) > 11.54$ and $\log(M_{200}/M_\odot) > 15$ are slow rotator candidates (red arrows).
In this Chapter I summarise the results of the research presented in this thesis. I discuss how this research fits into the broader context of galaxy evolution studies and assess the open questions that still need to be answered. Finally, I propose future projects to address those open questions.

5.1 Summary of the results

Chapter 2 presents a statistical analysis of the stellar mass growth of brightest group and cluster galaxies (BGG/BCGs) over the last 3 billion years ($z < 0.3$). From a large GAMA sample of 883 BGG/BCGs I find that the stellar mass of these galaxies is correlated with the mass of their host halos by $M_\star \propto M_{\text{halo}}^{0.32 \pm 0.09}$. This $M_\star - M_{\text{halo}}$ relationship suggests that BGGs and BCGs at $z < 0.3$ grow in step with their host systems but at a slower rate. To measure the stellar mass growth in the last 3 billion years ($z < 0.3$) taking this relationship into account, I compare the BGG/BCGs at lower redshifts ($z < 0.17$) to the BGG/BCGs hosted by potential cluster progenitors at higher redshifts ($0.17 < z \leq 0.27$). I find that the stellar mass growth in this redshift range is not significant ($0 \pm 9$ percent).

In Chapter 2 I also explore the star formation (SF) and Active Galactic Nuclei (AGN) activity of BGG/BCGs since $z \sim 0.3$. A fraction of 0.54 of the GAMA sample show Hα in emission. From those BGG/BCGs, a fraction of 0.27 are star-forming and 0.27 are AGN (Kewley et al. 2001). The fraction of AGN activity ($\sim 0.25 \pm 0.05$) in this GAMA sample is almost constant with stellar and halo mass, increasing slightly at the high stellar mass end ($0.3\pm0.05$). The fraction of star-forming galaxies in the GAMA sample decreases with increasing stellar mass. Thus BGGs are more likely to harbour SF. The star formation rate (SFR) follows a similar behaviour, falling from an average of $8 \, M_\odot \, \text{yr}^{-1}$ to $1 \, M_\odot \, \text{yr}^{-1}$ with increasing stellar mass. From the fraction of the star-forming galaxies, 0.19 can be
identified as actively star-forming \((\log \text{sSFR}(M_\odot \text{yr}^{-1}) > -11; \text{McGee et al., 2011}).\)

Chapter 2 also examines the fraction of BGG/BCGs offset from the centre of their host cluster. The offset fraction is \(0.13 \pm 0.01\). By examining the properties of the halos hosting central and non-central BGG/BCGs, I find that the BCG position is a reflection of their host environment. The non-central BGG/BCGs are hosted by clusters with small dominance \((\Delta m_{1.2} < 1.0)\) in regions with high over-densities, suggesting that these clusters have gone through a recent merger. The non-central BGG/BCGs are a factor of 2 less massive than the central BGG/BCGs at a fixed cluster mass. This suggests that central BGG/BCGs are well established galaxies which have accreted more mass than non-central BGG/BCGs. The SF and AGN fraction does not change between central and non-central BGG/BCGs, suggesting that non-central BGG/BCGs are drawn from similar populations to central BCGs, i.e. they used to be central galaxies in the past, but of less massive systems.

To explore the recent accretion histories of BCGs, Chapter 3 presents the spatially-resolved stellar populations of 10 BCGs selected from the SDSS. These BCGs are central galaxies and the sample can be described as 3 control galaxies (with no close companions within 10 kpc), 7 galaxies with close companions and 3 out of those 7 with major companions. I find that these galaxies have homogeneously high central metallicities \([\text{Fe/H}]_{[\alpha/\text{Fe}] = 0} = 0.13 \pm 0.07\), high central \(\alpha\)-enhanced ratios \([\alpha/\text{Fe}] = 0.24 \pm 0.03\), and shallow metallicity gradients \((\Delta [\text{Fe/H}] = -0.11 \pm 0.1)\). However, a 0.67 fraction of the galaxies in the sample have intermediate (5 to 9 Gyr) central ages and 0.33 have old central ages (> 10 Gyr). This suggests a range of evolutionary paths in BCGs. The distribution of those ages is also significantly different from the ages seen in the early-type galaxies of the ATLAS3D sample \(\text{McDermid et al., 2015}).\)

Chapter 4 examines the angular momentum of central BCGs as a function of galaxy structure (stellar mass and size) and environment (halo mass and dominance). The \(M_* - M_{\text{halo}}\) relationship appears to have some effect on the the angular momentum in BCGs. Above \(\log M_*(M_\odot) = 11.3\) and \(\log M_{\text{halo}}(M_\odot) = 15\) I do not observe fast-rotating BCGs. Chapter 4 also shows a relationship of BCG angular momentum with cluster dominance. Above \(\Delta m_{1.2} = 1.4\) all the BCGs are slow-rotators. These results add further evidence the strong connection between these galaxies and their environment.
5.2. Discussion

I discuss my results around the open questions presented in Section 1.3.

5.2.1 The stellar mass growth of BGG and BCGs

BGG/BCGs grow in step with their host clusters, this is known as the $M_\star - M_{\text{halo}}$ relationship. The GAMA sample presented in this research has a $M_\star - M_{\text{halo}}$ relationship slope of $b = 0.32 \pm 0.09$. This relationship is consistent with those found in previous studies at a similar redshift range (Lin & Mohr, 2004; Brough et al., 2008; Hansen et al., 2009). It is also shallower then the slope found by observations of BCGs at higher redshifts $z > 0.3$ ($b \sim 0.6$; Lidman et al., 2012; Bernardi et al., 2013; Ascaso et al., 2014; Kravtsov et al., 2014). However, the comparison between the relationships measured by different observations is not straight forward due to intrinsic systematic errors in the $M_\star$ and $M_{\text{halo}}$ estimations (Coupon et al., 2015; Han et al., 2015), as well as the methods used to measure the slope of the relationship. Therefore, the evolution of the $M_\star - M_{\text{halo}}$ relationship with redshift cannot yet be confirmed by observations.

Halo-abundance models have predicted the evolution of the $M_\star - M_{\text{halo}}$ relationship with redshift, however, these predictions are not in agreement. Moster et al. (2013) predicted a shallower slope with increasing redshift, while other models favour a steeper slope with increasing redshift (e.g. Yang et al. 2012; Shankar et al., 2014; Rodriguez-Puebla et al., 2015). Figure 5.1 illustrates a comparison between current observations and halo-abundance models. Shankar et al. (2014) model proposed an intrinsic scatter of 0.15 in stellar mass (at fixed halo mass) in order to match the observations. They found that the $M_\star - M_{\text{halo}}$ relationship evolves with redshift from 0.7 at $z \sim 1$ to 0.3 at $z \sim 0$. This would suggest that BCGs grow rapidly along with the cluster at high redshift, slowing down at low redshift.

The $M_\star - M_{\text{halo}}$ predicted growth with redshift by Shankar et al. (2014) is consistent with observations of BGG/BCG (Figure 5.2). Inagaki et al. (2014) found a stellar mass growth of 14 percent between $z = 0.4$ and $z = 0.2$ from a sample of BCGs selected from the Planck Sunyaev-Zeldovich cluster catalog (Sunyaev & Zeldovich, 1970; Ade et al., 2014). Zhang et al. (2015) analysed the stellar mass growth in 106 BCGs from the Dark Energy Survey (DES; Flaugher et al., 2012) finding little growth in the BCG stellar mass (8 percent) since $z \sim 0.3$. 


Figure 5.1: Reproduction of Figure 2 from Shankar et al. (2014) showing the comparison between models and observations on the $M_\star - M_{\text{halo}}$ relationship. Each panel represents a different redshift. Each study is labeled. $\beta$ are the typical slopes. Overall most of the observations and models lie above the Moster et al. (2013) model indicating steeper slopes. The $M_\star - M_{\text{halo}}$ relationship in the GAMA sample agrees with the observations of Bernardi et al. (2013).

The consistency between halo-occupation models and observations regarding BCG growth suggests that some physical process in BCG evolution is being overlooked or not properly modelled by SAMs (and dark-matter only simulations). One hypothesis is that the merger efficiency at low redshifts is lower. In this hypothesis a significant fraction of merging galaxies is stripped into the intra-cluster medium rather than merged with the BCG (e.g. Conroy et al. 2007; Coccato et al. 2011; Bernardi et al. 2011).

Evidence for this hypothesis comes from the analysis of BCG light profiles of Lauer et al. (2014) and Bai et al. (2014) who find that the Luminosity–$\sigma$ (Faber-Jackson Relationship) flattens with increasing aperture size used to measure the luminosity. From this they inferred that BCGs form in group environments (due to the low velocity dispersions of
5.2. Discussion

Figure 5.2: Reproduction of Figure 4 from Lin et al. (2013) showing the BCG stellar mass growth since $z = 1.5$. The blue symbols are the observations from Lin et al. (2013). The green triangles are from the SAM of Guo et al. (2011). The black points are local BCGs with the mean value represented as the purple star. There is good agreement between the observations and the model down to $z \sim 0.5$.

these systems) which then fall into clusters. This process will change their outer envelopes without changing their central regions (dissipationless mergers). Therefore, the galaxies would significantly grow in size rather than in stellar mass.

**BGG/BCGs growth compared to that of early-type galaxies**

BGG/BCGs are identified as extremes in the galaxy population and there is an ongoing debate regarding whether these galaxies are simply massive elliptical galaxies or whether they follow distinctive accretion histories. I discuss this question below.

Bernardi et al. (2010) and Bernardi et al. (2013) showed from the luminosity – morphology and size – mass relationship of SDSS galaxies, that BCGs are less concentrated and have more complicated (not simply explained by the de Vaucouleur law) luminosity profiles than other early-type galaxies. They suggest this is consistent with signatures of
recent mergers in BCGs. Lauer et al. (2014) showed that the Luminosity – $\sigma$ relationship (Faber-Jackson) from the inner parts of BCGs is comparable to that of early-type galaxies, $\sigma \propto L^{1/4}$, however, when the total luminosity is used (extending to the outer regions) the Luminosity – $\sigma$ relationship flattens for BCGs, $\sigma \propto L^{1/6}$. Bai et al. (2014) compared the growth of BCGs in a redshift range $0.9 > z > 0.3$ with the growth of early-type galaxies in the same cosmic time, finding that early-type galaxies are slightly smaller across cosmic time, however, they grow at similar rate. They conclude that the difference between BCGs and early-type galaxies lies in the outer regions of their luminosity profiles rather than the central regions, consistent with Lauer et al. (2014). The early-type galaxy luminosity profiles are steeper (more centrally-concentrated) than those of the BCGs.

Vulcani et al. (2014) compared the dynamical scaling relations of BGG and early-type galaxies from the COSMOS survey. They find that while the BGGs have in general larger radii than the early-type galaxies, the $M_* - \sigma$ relation is the same for both galaxies at $z \sim 0.6$. However, at low redshifts the scaling relations are significantly different between BCGs and early-type galaxies. They suggest that the accretion by mergers is more pronounced in BCGs from $0 < z < 0.6$ especially in the outer regions, than in normal early-type galaxies.

Overall, observations infer that BGCs and early-type galaxies might grow at similar rates, but that BCGs have more complex accretion histories reflected in their outer regions.

5.2.2 BGG/BCG star formation and AGN activity in the local Universe

In Chapter 2 I find that a fraction of 0.27 of the BGG/BCGs from the GAMA sample are AGN. This fraction does not change with stellar or halo mass. This result is consistent with the results of Stott et al. (2012) who found a constant fraction of AGN in BCGs across stellar mass and environment. Many BCG studies have found a higher probability of AGN activity in these galaxies compared to other galaxies in clusters (von der Linden et al., 2007; Lin & Mohr, 2007; Best et al., 2007; Kale et al., 2015; Chiaberge et al., 2015). AGN activity appears to be correlated with the gas reservoir found in cool-core clusters (Best et al., 2007; Kale et al., 2015). Cool-cores appear to be correlated with $H_\alpha$ in emission (Edwards et al., 2007). However, the reason for this AGN activity in BCGs and its connection with host cluster merging status is still an open question.

I also find a fraction of 0.27 of the BGG/BCG in the GAMA sample are star-forming, and
this fraction decreases with increasing stellar mass. This is consistent with models (e.g. Yang et al., 2013) and observations (e.g. Peng et al., 2010; Wijesinghe et al., 2012) of the wider galaxy population, where star formation rate is observed to increase with increasing stellar mass up to $\sim 10^{10} M_\odot$ after which the star formation rate decreases with increasing stellar mass. The BGGs show a bimodal distribution of passive and star-forming galaxies similar to that seen in the general population of galaxies. In contrast, the more massive BCGs are mostly passive. Recent observations of BCGs have found similar fractions of star formation (Liu et al., 2012; Fraser-McKelvie et al., 2014). Fraser-McKelvie et al. (2014), in agreement with this analysis, found that most of the 245 BCGs in their sample have SFR $< 10 M_\odot \text{yr}^{-1}$. Therefore, the contribution of star formation to the growth of stellar mass in BCGs at low redshift is not significant. This supports the hypothesis of BCG stellar mass growing predominantly by dissipationless mergers at low redshifts.

5.2.3 Properties of central and non-central BGG/BCGs

Chapter 2 shows that a fraction of 0.13 of the BGG/BCGs in the GAMA sample are offset from their cluster centre. This is in contrast with the expectation that the brightest galaxy is always the central galaxy (e.g. SAMs of Cole et al., 2000; Hatton et al., 2003; Baugh, 2006; Monaco et al., 2007; De Lucia & Blaizot, 2007; Somerville et al., 2008). However, it is in agreement with other observational studies which found similar fractions of clusters with non-central BCGs (e.g. von der Linden et al., 2007; Coziol et al., 2009; Skibba et al., 2010; Lauer et al., 2014). Lauer et al. (2014) observed that in clusters with low dominance, the BCGs and the second brightest galaxy have similar luminosity profiles. The non-central BGG/BCGs in the GAMA sample reside in halos that are likely to have undergone recent cluster-cluster mergers (low dominance).

The numerical simulations of Martel et al. (2014) show the cosmological history of 18 massive clusters, where the changes in relative BCG position are directly linked to cluster-cluster major mergers. Figure 5.3 illustrates the evolution of one of their simulated clusters. This cluster goes through a major merger of 3 progenitors at $z \sim 0.55$ leaving one of the progenitor central galaxies 2.2 Mpc away from the new centre. This galaxy is now the BCG of the remnant cluster which by dynamical friction will eventually fall to the new centre. From their results we can infer that non-central BCGs in observations simply reflect the cluster evolutionary state. This is in agreement with the results in Chapter 2, the non-central BGG/BCGs used to be central galaxies. However, observations have not examined yet whether the brightest galaxy and the central galaxy in clusters with offset
BCGs were formed in different substructures.

Figure 5.3: Reproduction of Figure 9 from Martel et al. (2014), evolution of a simulated cluster. Each panel represents a different redshift. The panels show dark matter (black), massive galaxies $> 10^{10} \, \text{M}_\odot$ (yellow dots), BCG (green dots), centre of the cluster (purple cross). The numbers in the upper left panel are the percentage of mass contribution of each progenitor cluster. Each panel is 8 Mpc $\times$ 8 Mpc (not comoving). The relative position of the BCG changes with cluster-cluster mergers.
5.2. Discussion

5.2.4 Accretion histories of BCGs from their spatially-resolved stellar populations

In Chapter 3 I find that BCGs have high central metallicities and $\alpha$-enhanced ratios, as well as shallow metallicity gradients. However, there is a large dispersion in the BCG central ages, suggesting a range of evolutionary paths in these galaxies. The old central ages are consistent with galaxies which formed rapidly at high redshifts ($z \sim 2$) which have evolved passively since, while the intermediate ages infer a continuous SF to $z \sim 1$.

Loubser et al. (2009) also found a bimodal distribution of BCG central ages (Figure 5.4). Ultraviolet and infrared observations (Wen & Han 2011; Hoffer et al. 2012; Donahue et al. 2015) found a bimodal distribution of passive and active star-forming BCGs at higher redshift ($z \sim 0.8$). However, it is still unknown if the intermediate to young ages in BCGs are a result of dissipational mergers at $z > 1$, or if they are connected to clusters with cooling gas at those epochs (e.g. cool-cores). Further analysis is needed to explore the star formation histories of these particular BCGs rather than the ages and metallicities of their most luminous stellar populations.

Figure 5.4: Reproduction of Figure 7 from Loubser et al. (2009), BCG central stellar age distribution. This figure compares the ages of BCGs from Loubser et al. (2009) cyan bars) with the early-type galaxies of Sánchez-Blázquez et al. (2006a red bars) and Thomas et al. (2005 grey bars) over the same mass range. Note the bimodal distribution in the BCGs in contrast with the early-type galaxies.
Comparison with the stellar populations of massive early-type galaxies

Cross et al. (2004) studied the luminosity function and the stellar populations from the photometric colours of early-type galaxies, at high (0.5 < z < 0.75) and low redshift (0 < z < 0.5). They found that early-type galaxies have short star formation timescales at z > 2 and have evolved passively since. This is confirmed by observations of the stellar populations of local early-type galaxies. Sánchez-Blázquez et al. (2006a) from a large sample of 98 early-type galaxies found that early-type galaxies in high-density environments are older and have higher metallicities than early-type galaxies in low-density environments.

Analysis of the average stellar populations of larger samples from the SDSS have found that BCGs are on average slightly younger (∼ 10 Gyr) than cluster early-type galaxies (> 10 Gyr; Bernardi et al. 2011; Fitzpatrick & Graves 2014; La Barbera et al. 2014). This is confirmed by the IFS observations of the MASSIVE survey (?) which found an average age in BCGs of ∼ 10 Gyr. These intermediate ages are not seen in massive early-type galaxies. Observations suggest that BCGs have various accretion histories. The bimodal distribution seen by Loubser et al. (2009) and this analysis are in agreement with the intermediate average age in BCGs observed by the stacked spectra of the SDSS and MASSIVE galaxies. Therefore, while some BCGs follow a similar evolution to massive early-type galaxies residing in high-density environments, others are very different.

5.2.5 The role of environment on the angular momentum of BCGs

In Chapter 4, I find that the angular momentum of the BCG reflects the current merging status of its host halo. Slow rotator BCGs are generally massive galaxies hosted by massive clusters, while fast rotator BCGs are generally less massive galaxies hosted by groups. This agrees with the expectation that massive BCGs are the end product of hierarchical structure evolution.

Chapter 4 also shows that recent cluster-cluster mergers can affect the BCG angular momentum. Massive fast-rotating BCGs are hosted by clusters with small dominance values (< 0.5). In contrast, the less massive slow rotators in the sample are hosted by groups with large dominance (> 1.4). This is in agreement with the results of Fogarty et al. (2014) who found that the BCGs in the clusters Abell 168 and 2399 are fast-rotating, and that these clusters show signs of recent cluster-group mergers.
Cappellari (2013) showed that early-type galaxies evolve from fast rotators to slow rotators in step with the size – stellar mass relationship (Figure 5.5). Galaxies above log $M_\ast (M_\odot) > 11.3$ tend to be slow rotators. Chapter 4 shows that the angular momentum of central galaxies behaves similarly to early-type galaxies in the size – stellar mass relationship. However, BCGs also depend on their host environment.

Larger samples covering a wide host halo range are needed to confirm these results. This will be possible to achieve with the new generation of IFS surveys: SAMI (Bryant et al., 2015), MaNGA (Bundy et al., 2014). Also, the connection between the BCG angular momentum and the angular momentum of the host cluster is still to be explored. New IFS instruments with better resolution and wider FOV, such as, MUSE, will allow a spatially complete study of the angular momentum of cluster galaxies.

![ATLAS$^{3D}$ Field and Coma Cluster](image)

Figure 5.5: Reproduction of Figure 4 from Cappellari (2013), dependence of the galaxy angular momentum with the size – mass relationship. The left-hand panel shows the field galaxies in the ATLAS$^{3D}$ sample. The right-hand panel shows the galaxies in the Coma cluster. The blue dash-dotted line represents the upper limit of spiral galaxies. The solid red line represents the lower limit of early-type galaxies. The dashed line represents the critical mass described in the text. The arrows show the evolutionary tracks: from spiral to fast rotator early-type galaxy, from fast rotator early-type galaxy to slow rotator early-type galaxy. All the slow rotators in the Coma cluster are beyond the critical mass and show an evolution with the size – mass relationship.


5.3 Summary and Conclusions

BCGs, in general, appear to acquire the majority of their stellar mass at high redshifts with their growth slowing down significantly at lower redshifts ($z < 0.3$). This is supported by observations of BCG stellar mass growth and the stellar mass – cluster halo mass relationship, which appears to be steeper at higher redshifts. It has been suggested that the slow down in stellar mass growth in BCGs is due to a decrease in the merger efficiency at low redshift, where some of the material from the in-falling galaxy is scattered into the intra-cluster medium. This is also consistent with these mergers not affecting the central (within $1 \, R_e$) stellar kinematics and stellar populations of BCGs. Some of the BCGs at present epochs show star formation activity, however, the star formation rates are low and do not contribute significantly to the stellar mass growth of these giant galaxies in the last 3 billion years.

BCGs and massive early-type galaxies appear to have similar high central metallicities and shallow inner metallicity gradients at present epochs. However, BCGs have more complex accretion histories, which is reflected in the wide range of central ages observed in BCGs. These ages are not apparent in massive early-type galaxies.

This thesis also shows that the position of BCGs with respect to their host dark matter halo and its angular momentum are directly connected to the evolutionary stage of its cluster. I show that non-central BCGs are consistent with being central galaxies that have fallen in through group mergers. BCGs hosted by groups also have higher probabilities of being fast-rotating than BCGs hosted by massive clusters. Simulations predict slow-rotating galaxies to have undergone many mergers such that these observations confirm massive BCGs as the final end product of the hierarchical formation scenario.
5.4 Future work

5.4.1 Unanswered Questions

1. Does the cluster merging status affect AGN activity in BCGs?

2. Are the stellar populations of non-central BCGs different to the stellar populations of the central galaxy?

3. What are the star-formation histories of BCGs with intermediate central age?

4. Is the angular momentum of BCGs aligned with the cluster angular momentum?

Answering these open questions requires the next generation of IFS observations, which will provide much larger samples of galaxies. These are described below:

Upcoming IFS surveys will address the problem of small spatial coverage as well as providing larger, statistically significant, samples. The Sydney-Australian-Astronomical-Observatory Multi-object Integral-Field Spectrograph (SAMI; Bryant et al., 2015) galaxy survey now underway, uses a new multi-fibre technique to observe up to 13 galaxies in one exposure. This survey will gather spatially-resolved spectroscopic information for ~3,000 galaxies selected from the GAMA survey. These galaxies are selected from a wide range of environments. Mapping Nearby Galaxies at APO (MaNGA; Bundy et al., 2014) is an upcoming IFS survey which will cover a galaxy population of unprecedented size (10,000 galaxies). In the longer term the proposed HECTOR (Bland-Hawthorn, 2015) instrument aims to observe ~100,000 galaxies.

In contrast, several smaller surveys will observe galaxies to larger radii. The SAGES Legacy Unifying Globulars and GalaxieS (SLUGGS Brodie et al., 2014) survey aims to cover up to 10 R_e in a limited sample of 25 early-type galaxies. MASSIVE (Ma et al., 2014) is a multi-wavelength IFS survey dedicated to massive early-type galaxies (M_*>10^{11.5} M_\odot) covering a volume-limited sample of 100 galaxies.

\[\text{SAMI: http://sami-survey.org/} \]
\[\text{MaNGA: http://www.sdss.org/surveys/manga/} \]
\[\text{SLUGGS: http://sluggs.swin.edu.au/Start.html} \]
5.4.2 BCG AGN activity and cluster status

Kale et al. (2015) presented a sample of 59 BCGs in X-ray clusters with radio-loud and -quiet AGN. They found that 71 percent of the radio-loud BCGs reside in relaxed clusters and 81 percent of radio-quiet AGN reside in merging clusters. They suggest that relaxed clusters might have cool-gas feeding the radio-loud AGN, while in a cluster-cluster merger this gas will be disrupted and the radio-loud AGN will disappear.

Best et al. (2007) also showed that some AGN with radio emission also have optical emission (11 out of 19 in their sample). I will use the sample of BCGs hosting AGN found in Chapter 2 to investigate the connection between optical AGN activity and cluster dominance. Which will explain the AGN feedback cycle with respect to its host cluster environment. This sample can further be extended using data from the SAMI survey.

5.4.3 Stellar populations of central galaxies in clusters with non-central BCGs

To investigate whether or not central galaxies in clusters with offset BCGs were formed in different substructures, I will investigate the central galaxies in the GAMA groups and clusters with non-central BCGs (N = 117). I will use the stellar population catalogue of Gallazzi et al. (2005) to compare the central stellar populations of the central galaxies with the non-central BCGs. From the results I can infer whether the central galaxy and the BCG have similar origins or not. I can also compare any difference in their stellar populations with the dominance, mass, and multiplicity of the clusters along with other properties provided by the GAMA survey. This will allow me to analyse cluster evolution through the stellar population of these massive galaxies.

5.4.4 Star formation histories of intermediate age BCGs

Chapter 3 shows that a fraction of BCGs have intermediate central ages (5 to 9 Gyrs). This suggests that these galaxies had continuous star formation down to \( z \sim 1 \). I will analyse the star formation histories of a representative sample of BCGs with central intermediate ages using IFS observations. The sample will be selected from the BCGs in Chapter 3 Loubser et al. (2009), and the stellar population analysis of the SAMI survey (Scott et al., in prep). I will also observe BCGs with old central ages as control galaxies. The galaxies will be observed with the KOALA IFS on the Australian Astronomical Observatory to ensure a large FOV. The star formation histories will be measured using the full spectrum
fitting technique, from the stellar population code STARLIGHT (Cid Fernandes et al., 2005). The results from this study will confirm whether younger central ages in BCGs represent distinct accretion histories or whether it is simply a stochastic effect (“frosting”). I will also explore the connection between these intermediate ages and clusters hosting cool-cores.

5.4.5 Angular momentum of BCGs

Chapter 4 demonstrated for the first time the connection between BCG angular momentum and its host cluster environment. However, larger samples and simulations are needed to confirm these results and better understand this connection. New IFS instruments such as MUSE offer the opportunity of observing not only the central galaxies but also their cluster companions in one exposure. Using MUSE I will measure the angular momentum of individual galaxies as well as the angular momentum of the cluster as a whole (by observing the kinematics of all the galaxies in the cluster). This will show whether BCG angular momentum is aligned with the angular momentum of their host clusters.


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