Galaxy stellar populations and dynamics as probes of group evolution

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"I love deadlines. I like the whoosing sounds they make as they fly by."

Douglas Adams
Abstract

The distribution of galaxy properties in groups and clusters holds important information on galaxy evolution and growth of structure in the Universe. While clusters have received appreciable attention in this regard, the role of groups as fundamental to formation of the present day galaxy population has remained relatively un-addressed. In this thesis we focus on the detailed analysis of properties in a single massive group, NGC 5044, with the aim of reconstructing its formation history. New observations obtained using the Anglo-Australian Telescope and the multi-object fibre-fed AAOmega spectrograph are combined with available photometry and X-ray data, which are used to construct a significant catalogue of spectroscopically confirmed group-member galaxies down to \( M_B \approx -13.5 \). We define the NGC 5044 group as hosting 111 spectroscopically confirmed member galaxies and a total dynamical mass of \( 9.2 \times 10^{13} M_\odot \). Of these 111 members, 67 have spectra from AAOmega and the 6dF Galaxy Survey of sufficient signal-to-noise to undertake a detailed investigation of their stellar populations.

We find that galaxies in the NGC 5044 group show evidence for a strong relationship between stellar mass and metallicity, consistent with their counterparts in both higher and lower mass groups and clusters. In the context of the group environment, our data support the tidal disruption of low-mass galaxies at small group-centric radii, as evident from an apparent lack of galaxies below \( \sim 10^9 M_\odot \) within \( \sim 100 \text{ kpc} \) of the brightest group galaxy. Using a joint analysis of absorption- and emission-line metallicities, we show that the star-forming galaxy population in the NGC 5044 group appears to require gas removal to explain the \( \sim 1.5 \text{ dex} \) offset between absorption- and emission-line metallicities observed in some cases. A comparison with other stellar population properties suggests that this gas removal is dominated by galaxy interactions with the hot intragroup medium. The combination of galaxy dynamics, stellar populations and X-ray chemical abundances lead us to the conclusion that the bulk of the NGC 5044 group assembled at early times through the coalescing of several smaller sub-groups, and has since evolved through relatively steady accretion of isolated galaxies or loose groups.
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Finally, to my family — John, Luan and Clayton, who have provided unending love and support regardless of how far away I’ve been. I can never thank you enough for your encouragement to pursue my interests during university, postgrad and in the future.
Declaration

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. All work presented is primarily that of the author.


Minor alterations have been made to these works in order to maintain consistency of style.

Jon Trevor Mendel
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Introduction

Since the 1930’s it has been recognised that galaxy morphologies are not distributed uniformly across the sky; bulge-dominated, red elliptical and S0 galaxies — referred to as ‘early-type’ — are preferentially found where galaxies are more highly clustered (e.g. Hubble and Humason, 1931) while disk-dominated, blue spiral galaxies — referred to as ‘late-type’ — occupy the low-density ‘field’ environment. Oemler (1974) and Dressler (1980) were the first to quantify the variation of morphological fraction between high-density clusters and low-density field environments, establishing the morphology–radius and morphology–density relations, respectively. Postman and Geller (1984) extended the morphology–density relation to include galaxies in low space densities and found that the cluster morphology–density relation held over more than six decades in local galaxy density, from loose groups to the rich clusters probed by Oemler (1974) and Dressler (1980).

More recently, large spectroscopic and photometric surveys have enabled an increasingly detailed study of the environmental dependence of galaxy properties. It is now well established that, in addition to preferentially early-type morphologies, the galaxy populations of clusters are on average redder in colour, more centrally concentrated, more massive, older and more metal-rich than their low-density field counterparts (e.g. Goto et al., 2003; Blanton et al., 2005; Bernardi et al., 2006; Blanton and Berlind, 2007; Park et al., 2007; O’Mill et al., 2008; Cooper et al., 2008; van der Wel, 2008). Despite significant observational evidence for environmental dependence in the galaxy population, the physical cause of this dependence remains unclear. There are generally considered to be two separate paths by which the observed environmentally-dependent properties can be established:
Chapter 1. Introduction

In the first — the *nature* scenario — galaxies observed in high-density regions experience a fundamentally different formation at early times, and the observed morphology–density relation is therefore established *at the epoch of formation*. In such a biased formation scenario (e.g. Cen and Ostriker, 1993), high-density regions in the primordial matter-density distribution collapse earlier, more rapidly and host preferentially more massive galaxies relative to low-density regions.

In contrast, the alternate, *nurture* scenario can explain well the observed distribution of galaxy morphologies and structural properties. In this scenario, galaxies form with no predisposition towards being found in the field or a cluster at redshift zero. Instead, the morphology-density relation is built up via interactions of galaxies with their surroundings — either with other galaxies or their large-scale environment — which truncate star formation and disturb the morphologies of disk-dominated, rotationally supported late-type galaxies, producing an early-type-dominated population in clusters.

Perhaps unsurprisingly, observational evidence suggests that both *nature* and *nurture* play important roles in formation and evolution of the galaxy population.

1.1 Nature vs. Nurture

Nature

The numerous, tight scaling relations between the photometric and structural properties of early-type galaxies suggests they are set in place relatively early on in the formation of the early-type galaxy population, rather than generated through stochastic evolution via environmental interactions.

The existence of a tight relation between galaxy colour and absolute magnitude for early-type galaxies has been known for several decades (Baum, 1959; Visvanathan and Sandage, 1977). In an effort to quantify the ubiquity of the colour–magnitude relation (CMR), Bower et al. (1992) used multi-band photometry of the Coma and Virgo clusters to show that both the slope and position of the CMR is invariant from cluster to cluster. Subsequent photometric studies over a broader range of environments have shown that early-type galaxies form uniform sequence in colour-magnitude space — the so-called ‘red sequence’ in the CMR — with only limited
1.1. Nature vs. Nurture

dependence on environment (e.g. Hogg et al., 2004; Gallazzi et al., 2006).

In the late 1970’s, Faber and Jackson (1976) showed a correlation between magnitude and line-of-sight velocity dispersion for a sample of elliptical galaxies; soon after, Kormendy (1977) identified the apparent relationship between galaxy size and surface brightness. In similar studies of galaxy properties, Djorgovski and Davis (1987) and Dressler et al. (1987) pointed out that the two-dimensional Kormendy and Faber-Jackson relations are actually projections of a tight three-dimensional relationship between galaxy radius $r_e$, central velocity dispersion $\sigma$ and surface brightness $I_e$. This “Fundamental Plane” (FP) of galaxy properties provides compelling evidence in favour of a uniform formation scenario for early-type galaxies. Theoretical derivations of a virial FP — i.e. based solely on the virial theorem — predict the interdependence of $r_e$, $\sigma$ and $I_e$ to follow

$$\log r_e = 2 \log \sigma - \log I_e + \log (M/L)_e + C,$$

(1.1)

where $C$ is a constant. Under the assumption of homology in the early-type galaxy population, Eqn. 1.1 predicts that a relationship where $r \propto \sigma^2 I_e^{-1}$ fully describes the early-type galaxy population. Observational constraints on the FP, however, suggest that the actual relationship is tilted with respect to the virial FP in such a way that $r \propto \sigma^{1.8} I_e^{-0.8}$ (Dressler et al., 1987; Jorgensen et al., 1996; Pahre et al., 1998; Colless et al., 2001). This tilted plane is often taken as evidence of a systematically varying mass-to-light ratio ($M/L$ term in Eqn. 1.1) in the galaxy population, e.g. an increasing dark matter fraction with mass. However, stellar population dependence, structural non-homology and specific selection biases cannot be explicitly ruled out (Trujillo et al., 2004; Proctor et al., 2008).

Nevertheless, the Faber-Jackson relation, Kormendy relation and FP all provide evidence for a critical dependence of galaxy structural parameters on internally-governed processes which is echoed in other galaxy properties; there exist tight correlations between the masses of central supermassive black holes and the velocity dispersions of their host galaxies (e.g. Graham, 2008), between magnesium abundance and velocity dispersion (e.g. Worthey and Collobert, 2003) and between galaxy stellar mass or luminosity and metallicity (e.g. Tremonti et al., 2004; Gallazzi et al., 2006). Recent work by Spolaor et al. (2009) suggests that the observed tight relationships between galaxy properties may also extend to higher-order measure-
ments. Spolaor et al. find that low-mass early-type galaxies exhibit a remarkably tight relationship between central velocity dispersion and radial metallicity gradient in direct support of an internally governed, collapse model for these low-mass systems.

**Nurture**

Despite the strong evidence for a *nature*-driven formation scenario of early-type galaxies, significant observational evidence also exists for environmentally-influenced, *nurture*-based evolution.

The strongest evidence for environment playing an important role in the evolution of the galaxy population comes from the study of the galaxy star-formation rate (SFR). In a study using the 2dF Galaxy Redshift Survey (2dFGRS) and focused on cluster populations, Lewis et al. (2002) found that galaxies showed a dependence of SFR on cluster-centric distance whereby star-formation rates were depressed inside ~ 3 virial radii of the cluster core relative to the mean star-formation rates in field galaxies. In a corroborating study, Gómez et al. (2003) used the SDSS Early Data Release to show that galaxy SFR is a strong function of projected galaxy density. These results both identify surface densities of ~ 1 – 2 galaxies per Mpc$^2$ as a transition in the star-formation properties of field galaxies, corresponding to ~ 3 – 4 times cluster virial radii. Follow-up work on the star-forming properties of galaxies has supported a strong dependence of star-formation properties on environment, even independent of galaxy morphological type (Kauffmann et al., 2004; Blanton et al., 2005; Quintero et al., 2006).

In a series of papers, Kauffmann et al. (2003a, b, 2004) used a large sample of galaxies from the SDSS to undertake a study of galaxy properties and their environmental dependence. In addition to the large photometric sample provided by SDSS, Kauffmann et al. incorporated the λ4000 break, $D_n(4000)$, and the Balmer-absorption line HδA as spectroscopic age indicators. Through a comparison of $D_n(4000)$, HδA and normalised star-formation rate (SFR/$M_*$), Kauffmann et al. (2004) confirm the findings of Lewis et al. and Gómez et al. and show that, while star-formation rates fall, mean galaxy star-formation histories are relatively invariant with respect to local density. They interpret this observed invariance as indicative of a smooth decrease in the star-formation rates of in-falling cluster galaxies over
1.2. Observed evolution of the galaxy population

relatively long timescales, \( \gtrsim 1 \) Gyr or more. Subsequent studies of star-formation history have supported the conclusions of Kauffmann et al. (2004), providing important information regarding the timescales over which environment is apparently acting to suppress the galaxy star-formation rate (e.g. Kawata and Mulchaey, 2008; Cooper et al., 2008; van den Bosch et al., 2008).

In addition to suppressed star-formation rates, evidence also exists for the rapid truncation of star-formation activity in high-density environments. Poggianti et al. (2004) used a combination of X-ray imaging and optical spectroscopy to show a high incidence of post-starburst galaxies (E+A) in the Coma cluster corresponding with observed peaks in X-ray surface brightness. The E+A type galaxies observed by Poggianti et al. (2004) are similar in nature to so-called ‘passive spiral’ galaxies (Goto et al., 2003; Moran et al., 2007) — late-type galaxies with clear spiral morphologies but weak or non-existent star-formation — in that they require star-formation to be halted on short timescales of 100 – 400 Myrs, unlike the slow starvation observed by Kauffmann et al. (2004).

1.2 Observed evolution of the galaxy population

Disentangling the relative influences of nature and nurture processes is best approached by studying the evolution of the galaxy population with cosmic time, which provides a means of distinguishing between their differing predictions for how the galaxy population should evolve (i.e. passively vs. actively).

Butcher and Oemler (1984) first reported the correlation of late-type galaxy fraction with look-back time, using a sample of clusters to show a 10 – 15% increase in the fraction of blue galaxies in clusters at \( z \sim 0.5 \) relative to \( z \sim 0 \). Further study of the evolution of the morphological fraction in clusters has shown that decline of the late-type fraction since \( z \sim 0.5 \) is matched by a steep rise in the early-type fraction, accounted for almost entirely by an increase in the population of S0 galaxies (e.g. Dressler et al., 1997; Desai et al., 2007). Extending the study of morphological fractions to lower galaxy surface-densities, Smith et al. (2005), have shown that the evolution of morphological fraction is strongly dependent on local density; galaxies in rich clusters show a much stronger evolution of late-type fraction since \( z \sim 0.5 \) than galaxies in field environments. These observations closely tie the formation of S0
galaxies to the transformation of late-type galaxies, either through the suppression of star-formation and subsequent fading of the disk or the dynamical disruption of disks via minor mergers (e.g. Bedregal et al., 2006; Aragón-Salamanca et al., 2006). The results of Smith et al. (2005) further link S0 formation to environment.

Complementary constraints on the evolution of the galaxy population come from analyses of the luminosity function — that is, the galaxy number-density as a function of absolute magnitude — and its evolution with redshift. Early measurements of the luminosity function found that its evolution is closely tied to internal galaxy properties, namely colour, whereby blue star-forming galaxies account for the majority of number-density growth in the luminosity function since $z \sim 0.5$ (e.g. Lilly et al., 1995; Cowie et al., 1996). More recently, large photometric surveys have facilitated a much more accurate measurement of the high-redshift luminosity function. Faber et al. (2007) used a combination of DEEP2 and COMBO-17 photometry to show that the number density of red galaxies has increased by a factor of $\sim 3$ since $z \sim 1$ while the blue-galaxy number density has remained relatively constant. Faber et al.’s findings of strong evolution in the red galaxy population are in disagreement with earlier studies (e.g. Cowie et al., 1996), however coincident studies on the growth of stellar mass-density on the red sequence show quantitative agreement with a factor of 2 – 3 growth since $z \sim 1$ (e.g. Ilbert et al., 2006; Brown et al., 2007).

The relatively late growth of red galaxy number-density observed by Faber et al. limits the degree to which a purely formation-driven scenario (i.e. nature) can explain the observed properties of the galaxy population. Instead, their results support a scenario in which environmental processes, such as the quenching of star-formation discussed previously, must be playing a vital role in the build-up of the $z \sim 0$ galaxy population. Coupled with the observed evolution of early-type fraction in clusters (Dressler et al., 1997; Smith et al., 2005; Desai et al., 2007) and the suggested origin of S0 galaxies as ‘starved’ or ‘quenched’ spirals (e.g. Aragón-Salamanca et al., 2006), analyses of the luminosity function’s evolution highlight the study of environment-dependent processes as vital to our understanding of galaxy evolution.
1.3 Environmental dependence of external processes

In conjunction with the observed differences between galaxy populations in high- and low-density environments, the dependence of galaxy properties on environment motivates a more detailed consideration of physical processes acting in groups and clusters and the timescales over which they act. Here we consider a division of external properties into two categories: i) interactions which involve other galaxies and ii) interactions with the larger group or cluster environment.

1.3.1 Galaxy–galaxy interactions

It is now well established that structure grows hierarchically in the “concordance” ΛCDM cosmology (e.g. White and Rees, 1978; Somerville and Primack, 1999; De Lucia et al., 2006). Early work studying the interactions of disk galaxies showed that major mergers — i.e. those with mass ratios between 3:1 and 1:1 — are an efficient means of randomising stellar orbits and creating normal, bulge-dominated early-type galaxies (e.g. Toomre and Toomre, 1972; Hopkins et al., 2008). Furthermore, mergers are observed to play a fundamental role in the evolution of the galaxy population since at least \( z \sim 1 \) (Tran et al., 2005; McIntosh et al., 2008; Lotz et al., 2008a), and hence are inferred to be important to both the formation of elliptical galaxies and the growth of stellar mass in red galaxies at late times.

In the context of environmental dependence, the prevalence of mergers in a particular environment is most easily demonstrated through consideration of the galaxy merger rate. The approximate merger rate for equal-mass galaxies is a function of both the merging galaxy masses \( m \) and their relative velocities — dependent on the velocity dispersion on their host environment \( \sigma_s \) — such that the merger rate can be parameterised by (Mamon, 1992, 2007)

\[
k(m) \propto \frac{m^2}{\sigma_s^3}.
\]  

As shown in Eqn. 1.2, the merger rate is a strong function of both the mass of the merging galaxies and the velocity dispersion (i.e. mass) of the host environment in such a way that the merger rates of galaxies in clusters are several tens of times lower than that of similar galaxies in the group environment. While mergers provide an
effective means of disrupting late-type morphologies and stimulating the formation of bulge-dominated early-type systems, recent theoretical work has shown that the presence of gas in mergers, as in the case of low- and intermediate-mass galaxies or galaxies at high redshift, can serve to suppress the formation of a bulge component (e.g. Hopkins et al., 2009). Therefore, even theoretical models which predict multiple major mergers throughout a galaxy’s lifetime are able to match the observed morphology–mass trends (e.g. Balcells et al., 2007). However, a scenario in which late-type galaxies evolve only through mergers is incompatible with the observed predominance of early-type galaxies in high-density environments and the observed smooth trend of decreasing specific star-formation rate as a function of local density, even at densities where the merger rate falls dramatically (e.g. Lewis et al., 2002; Gómez et al., 2003).

A consequence of the strong inverse dependence of $k(m)$ on the galaxy–galaxy encounter velocity (as characterised by its dependence on $\sigma^3$) is that the merger rates in massive systems are very low. However, this is unrelated to the frequency of galaxy encounters, which rises in high-density systems. It has therefore been suggested that, rather than merger-driven disruption, numerous rapid tidal encounters can also efficiently disrupt the morphologies of late-type galaxies. So called “galaxy harassment” (Farouki and Shapiro, 1981; Moore et al., 1996) relies on impulsive tidal encounters to induce small velocity perturbations of order $\delta V \lesssim 50$ km s$^{-1}$ at random orientations to the disk. Several such encounters build an increasingly “puffy”, random-velocity supported component in the galaxy, drive secular evolution of a bulge component by inducing instabilities in the stellar disk and strip loosely bound stars from the galaxy outskirts. Due to its dependence on rapid encounters, harassment is only an effective evolutionary process in high-density, high-velocity-dispersion cluster environments.

1.3.2 Galaxy–environment interactions

The baryon budget of groups and clusters is dominated by the contribution of hot, X-ray emitting gas (e.g. Gonzalez et al., 2007). Galaxies interacting with the hot intra-group and intracluster medium (IGM/ICM) frequently show evidence for tidal tails, shocks and disruption in their cold gas distributions (White et al., 1991; Veilleux et al., 1999; Clemens et al., 2000; Vollmer et al., 2008), identifying gas removal via
1.3. Environmental dependence of external processes

ICM interactions as responsible for the observed of HI mass deficit in cluster galaxies (Giovanelli and Haynes, 1985). The removal of cold gas from star-forming galaxies effectively suppresses any on-going star formation, in agreement with previously discussed observations of declining star-formation rates as a function of projected galaxy surface density (Lewis et al., 2002; Gómez et al., 2003).

The slow exhaustion of gas necessary to reproduce the observed gradients in star-formation properties (Lewis et al., 2002; Gómez et al., 2003; Kauffmann et al., 2004, e.g.) out to large cluster-centric distances has led to the concept of ‘strangulation’ (Balogh and Morris, 2000), where infalling galaxies are stripped of their hot, extended gas reservoirs as they join the group or cluster environment. Bekki et al. (2002) have simulated the infall of late-type galaxies onto clusters, showing that even at $\sim 3$ core radii, the combination of weak IGM/ICM interactions and the global tidal field of the group or cluster is sufficient to strip $\sim 80\%$ of a galaxy’s gaseous halo.

Towards the group or cluster centre, galaxies moving through the ICM/IGM experience a wind related to the density of the IGM and their peculiar velocity relative to the cluster centre. Motivated by the observation of gas-poor galaxies in clusters, Gunn and Gott (1972) used a simple analytical relation to describe the effects of this wind on a galaxy’s gaseous halo, quantifying the conditions under which it is stripped as

$$\rho_{\text{ICM}} v_{\text{sat}}^2 \geq 2G \pi \Sigma_\ast \Sigma_g,$$

where $\rho_{\text{ICM}}$ is the density of the intracluster medium, $v_{\text{sat}}$ is the relative velocity of the galaxy through that medium and $\Sigma_\ast$ and $\Sigma_g$ are the stellar and gas surface densities, respectively. The relation suggested by Gunn and Gott (1972) is easy to understand in physical terms: when the ram pressure, quantified by $\rho_{\text{ICM}} v_{\text{sat}}^2$, exceeds the restoring force of the galaxy potential, gas is removed. Due to the strong dependence of Eqn. 1.3 on the density of the ICM/IGM, ram-pressure is most effective in high-density environments, such as cluster cores, where it can efficiently remove gas from even massive galaxies.

More recent studies have begun to show that ram-pressure stripping can be effective even at scales were the ICM was traditionally considered too diffuse. Hester (2006) used a numerical simulation involving galaxies with a range of masses moving
through several scales of environment — from a small group with \( M \approx 10^{13} M_\odot \) to a massive cluster with \( M \approx 10^{15} M_\odot \) — to show that even intermediate-mass disk galaxies in groups could be stripped of their gas to \( \sim 60\% \) of their disk scale-length.

This model is in agreement with a growing body of observational evidence for ram-pressure stripping in the group environment (Sivakoff et al., 2004; Machacek et al., 2005; Rasmussen et al., 2006; Kawata and Mulchaey, 2008).

Even in instances where ram pressure is insufficient to strip galaxies, such as for massive galaxies or low IGM/ICM densities, transport processes can still play a role in removing gas. Kelvin-Helmholtz Instability (KHI) at the interface between the interstellar medium (ISM) and the IGM/ICM can efficiently remove gas from galaxies. The mass-loss rate due to propagation of these instabilities is given by (Nulsen, 1982)

\[
\dot{M}_\text{KH} \approx \pi r^2 \rho_{\text{ICM}} v_{\text{sat}},
\]

where \( r \) defines the radial extent of the galaxy’s gaseous halo and \( v_{\text{sat}} \) the relative galaxy-IGM velocity. The environmental dependence of gas removal due to KHI given by Eqn. 1.4 is weaker than that of ram-pressure stripping (Eqn. 1.3) by a factor corresponding approximately to the system velocity dispersion. More importantly, turbulent stripping can efficiently remove gas from even massive galaxies in low density environments, where ram-pressure stripping may be largely ineffective, due to its lack of dependence on the stripped galaxy’s potential and strong dependence on linear size. KHI at the ISM–IGM interface is actually likely to dominate gas removal via galaxy–IGM interactions in the low-density regime, such as cluster outskirts and loose groups, where low IGM densities render ram pressure ineffective.

### 1.3.3 Timescales

An important consideration for the processes described above is the timescales over which they act, particularly given recent observational evidence which suggests that cluster galaxy star-formation histories are most consistent with the slow truncation of star formation over more than several Gyrs.

Tidal interactions — either galaxy–galaxy or galaxy–potential — operate over relatively long timescales, of order several Gyrs. Constraints on the observability of
tidal features, however, are significantly more uncertain. Recent hydrodynamic simulations suggest that major mergers may trigger long-lived bursts of star-formation, \( \gtrsim 1 \text{ Gyr} \), in remnant galaxies \{Lotz et al., 2008\}.

Given the nature of harassment, i.e. multiple tidal encounters, it provides no definite timescale over which either morphology or star-formation rates should be affected, but it is reasonable to assume that several crossing times are necessary for multiple encounters to take place. In addition, if bulge growth is tied to encounter-induced disk instabilities, then the build-up of a pseudo-bulge should proceed over several dynamical timescales; if instead tidal interactions trigger centralised bursts of star-formation \{Moore et al., 1996\}, then a bulge component is expected to build up over several Gyrs \{Kormendy and Fisher, 2008\}.

The efficiency of strangulation depends on the degree to which a galaxy’s halo is stripped, however in general the timescales over which a galaxy exhausts its remaining gas supply varies from one to several Gyrs.

The timescale over which ram-pressure stripping takes place varies significantly depending on ICM density and galaxy mass. Under the assumption that galaxies experience ram pressure strong enough to remove their entire gas reservoir, then the truncation of star formation in stripped late-type galaxies will proceed rapidly, over several hundreds of Myrs or less. However, a significantly more common occurrence is that only some portion of a galaxy’s gaseous halo will be removed, in which case a galaxy’s star-formation rate will slowly decline over timescales of several hundreds of Myrs to several Gyrs.

Gas removal via the propagation of instabilities in the galaxy halo will result in a decline of star-formation rate similar to that of partially ram-pressure stripped galaxies, of order several hundreds of Myrs to Gyrs depending on the severity of turbulent removal.

### 1.4 Clusters vs. groups

In the hierarchical paradigm of structure formation massive clusters are built up through successive infall of smaller systems. Given the above discussion regarding the particular environmental dependencies of both galaxy–galaxy and galaxy–environment processes, it is interesting to now revisit our initial question about the
Chapter 1. Introduction

driving force behind evolution along the Hubble sequence. Do group and cluster
galaxies show the expected signs of varied, environmentally-dependent evolution?

In fact, despite differing physical processes, studies relating group and cluster
galaxy populations find remarkable similarity between the two. Zabludoff and
Mulchaey (1998) used multi-object spectroscopy and a large photometric catalogue
to identify \(\sim 280\) confirmed group galaxies in 12 different loose groups, both X-ray
bright and undetected. Zabludoff & Mulchaey showed that the morphological mix
in groups, as measured by the fraction of early-type galaxies, varies significantly
from field- to cluster-like (\(\sim 25 \text{--} 55\%\); Zabludoff and Mulchaey 1998). However,
they emphasise a subsample of their groups which, despite having number densities
and velocity dispersions significantly below that found in rich clusters, show a sim-
ilar fraction of evolved, early-type galaxies. Zabludoff & Mulchaey’s findings have
been confirmed for X-ray bright groups (Helsdon and Ponman 2003). In a study
by Kodama and Smail (2001), it was suggested that hierarchical models actually
require infalling groups to host significant numbers of evolved galaxies in order to
match observed cluster populations.

The observed morphological similarity between groups and clusters has led to the
idea that galaxies are “preprocessed” in the group environment, i.e. the majority
of difference between observed cluster and field galaxy populations is driven by
galaxy evolution in the group environment prior to cluster infall (Zabludoff and
Mulchaey, 1998; Kodama and Smail, 2001; Zabludoff, 2002; Fujita, 2003). This
scenario is supported by the work of Helsdon and Ponman (2003) in their study of X-
ray bright groups, where they found the morphology-density relation to be stronger
in groups than clusters; an expected result if the observed cluster morphology-
density relation is simply a residual of a more “primordial” group relation. It is worth
noting, however, that observations of morphological fractions in groups at \(z \sim 0\) do
not necessarily constrain formation of the present-day cluster population due to
potentially unknown formation- and merger-history biases (e.g. galaxies or groups
which form the present-day cluster population may be unrelated to the present-day
group population). In an effort to address the question of formation bias, Kautsch
et al. (2008) obtained targeted observations of the supergroup SG1120-1202 — a
gravitationally bound set of groups or protocluster — at \(z \sim 0.37\) to unambiguously
constrain the morphological mix of a pre-assembled cluster at \(z \sim 0\). Kautsch et al.
1.4. Clusters vs. groups

(2008) show their results are consistent with the earlier findings of Zabludoff and Mulchaey (1998) and Kodama and Smail (2001), namely that the morphological mix of galaxies in SG1120 matches that of rich clusters (in their example, Coma) prior to assembly as a cluster. Kautsch et al.’s findings provide a strong observational underpinning to preprocessing as an important evolutionary mechanism.

Adopting preprocessing as a paradigm in describing the evolution of galaxy populations places strong constraints on mechanisms dominating the formation of early-type galaxies; most importantly it argues against processes which dominate at high-density scales such as ram-pressure stripping and harassment, although these cannot be ruled out as playing some part in galaxy evolution. It lends strong support to mergers as an important evolutionary pathway due to their prevalence in low-velocity-dispersion environments.

Despite the apparent observational agreement over preprocessing as driving the observed trends of galaxy properties with environment, there is still theoretical disagreement over whether or not group preprocessing plays a significant role in galaxy evolution. Berrier et al. (2009) have used a set of $N$-body simulations to trace the growth of clusters over cosmological timescales, finding that, on average, roughly 70% of galaxies in clusters are accreted directly from the field with no companions. Furthermore, Berrier et al. find that a significant fraction of their simulated clusters, $\sim 83\%$, form without accreting any galaxies from groups with 5 or more members. These findings are in stark disagreement with the comparison of morphological fractions discussed above. However, Berrier et al.’s findings are consistent with analyses of galaxy colours: van den Bosch et al. (2008), for instance, argue that their SDSS galaxies are best explained by a scenario where the act of galaxies falling into a larger halo, regardless of size, enacts a transformation from field- to cluster-like.

Ultimately, the determination of dominant mechanisms of galaxy evolution will only come from a detailed study of galaxy properties in both group and cluster environments. To date, clusters of galaxies have been relatively well studied due to their rich and conspicuous galaxy populations, whereas galaxy groups have been somewhat neglected. Overwhelmingly however, galaxies in the Universe are found in the group environment (Geller and Huchra, 1983; Eke et al., 2004; Weinmann et al., 2006), and their lack of study is more a result of their observational cost.
than their astrophysical interest. This thesis aims to address this question of galaxy evolution in the group environment by leveraging a combination of spectroscopic stellar population measurements and a complementary multiwavelength dataset to unambiguously determine the formation history of a rich group.

1.5 Thesis structure

The organisation of this thesis is as follows: in this chapter we have briefly described our current understanding of galaxy evolution and, in particular, its close-knit relation with environment. To date, studies with a focus on environment have primarily made use of cluster galaxy populations; the aim of this thesis is to fill the gap left by these studies by carrying out a deep spectroscopic analysis of the group environment. The remainder of the thesis is ostensibly separated into two parts.

In the first, we define our group sample and quantifying its dynamical properties. In Chapter 2 we introduce the group selected for study in this work, NGC 5044, and review relevant literature describing it. The bulk of literature on the NGC 5044 group is related to its X-ray properties, however these data also include HI observations, optical imaging and spectroscopy. We then go on to describe the specific data used in this work in terms of both new multi-object spectroscopic observations as well as supplementary literature data. For spectroscopic observations we describe the method used to derive their kinematics and how these compare to published values.

In Chapter 3 we define the group galaxy population using our greatly increased number of galaxy recession velocities and, using this redefined sample, seek to describe the NGC 5044 group’s dynamical characteristics. These data allow us to not only more than triple previous numbers of spectroscopically confirmed group members, but also analyse the dynamic and kinematic properties of galaxy sub-populations within the group.

In the second part of this thesis we turn to a discussion of stellar population measurements. In Chapter 4 we discuss the measurement of stellar populations using Lick index absorption features. Before applying this technique to our group data, we first gauge its reliability in recovering the ages, metallicities and $\alpha$-element abundances of known stellar populations, in this case Galactic globular clusters.
These data allow us to both analyse the reliability of the parameters derived from integrated spectra using Lick indices, as well as gauge the strengths and weakness of adopted single stellar population models.

In Chapter 5 we focus on characterising the stellar populations of NGC 5044 group galaxies, both as a galaxy population and with respect to their place in the group environment. This analysis includes not only galaxy absorption-line characteristics but, where available, seeks to incorporate measurable emission-line properties as well.

Finally, Chapter 6 summarises the findings of previous Chapters and draws together our full dynamical, kinematic and chemical picture of the NGC 5044 group. We reflect on what these data add to our understanding of galaxy evolution in the context of the group environment and discuss the prospects of future studies aiming to expand upon the work presented here.
In this Chapter we introduce the focus of this thesis, the NGC 5044 group. We first describe the group’s general properties as derived in the literature from a variety of multi-wavelength data. We then discuss the new data obtained for this work and the measurement of galaxy kinematics used throughout the remainder of this thesis, as well as the literature recession velocity data included in our analysis of the NGC 5044 group.

2.1 Group selection and previous work

As discussed in the previous Chapter, groups provide an interesting testing ground for the study of environmentally-driven galaxy evolution. The goal of this thesis is to undertake the detailed study of a single galaxy group using deep spectroscopic observations to disentangle the relative influences of formation and evolution — i.e. nature and nurture — in the group environment. We have selected the NGC 5044 group as the focus of this work based on two primary goals:

Firstly, we need to be able to observe a significant number of group members in order to compile a sufficiently large galaxy sample for analysis. Secondly, we aim to reach far down the luminosity function in order to probe the group’s population of dwarf galaxies, motivated by their importance as “building blocks” in the currently favoured paradigm of hierarchical formation. The relatively high mass of the NGC 5044 group, $\sim 2 - 7\times10^{13}$ $M_\odot$ (David et al., 1994; Buote et al., 2003, 2004; Betoya-Nonesa et al., 2006; Brough et al., 2006a) suggests that it hosts a significant galaxy population and is therefore well suited to our first requirement. In addition,
the group’s close proximity, \((m - M)_0 = 32.31\) mag (28.98 Mpc from surface brightness fluctuation measurements; \cite{Tonry2001, Jensen2003}), implies that we can observe a significant population of dwarf galaxies using available wide-field spectrographs.

Literature studies on the NGC 5044 group are numerous, owing to the group’s close proximity and high X-ray luminosity, and span a significant baseline in wavelength coverage. As part of the Group Evolution Multi-wavelength Survey (GEMS; \cite{Osmond2004, Forbes2006}) NGC 5044 was studied along with 60 other groups using a compilation X-ray, optical and radio data. As part of the study of Southern GEMS groups, \cite{Brough2006a} have defined the dynamical properties of the NGC 5044 group using optical data from the 6dF Galaxy Survey (6dFGS; \cite{Jones2004}) and NASA/IPAC Extragalactic Database (NED). \cite{Brough2006a} use a friends-of-friends algorithm (\cite{Huchra1982}) to define the NGC 5044 group as having 35 spectroscopically confirmed members with a total dynamical mass of \(6.9 \times 10^{13} M_\odot\). Additionally, they find the group to be relaxed with a relatively short crossing time, although it is worth noting their sample is primarily limited to bright galaxies due to the \(K\)-band magnitude limit imposed by the 6dFGS (which constitutes the majority of their sample).

While the work of \cite{Brough2006a} is more recent, the most relevant optical study to the work presented in this thesis is that of Ferguson & Sandage (1990; 1991, hereafter FS90 and FS91 respectively), who photometrically studied 7 nearby groups and clusters, including NGC 5044, constructing group luminosity functions and examining the relative fractions of dwarf and giant galaxies. FS90 observed the NGC 5044 group using photographic plates covering \(\sim 2.3\) deg\(^2\) taken at the 2.5m duPont Telescope at the Las Campanas Observatory and used a \(B\)-band radial cut of 16" — estimated to be 27 mag arcsec\(^{-2}\) at the distance of NGC 5044 — to select potential member galaxies and limit background contamination. Group membership was then defined using morphological criteria to differentiate between background galaxies and genuine group members. The FS90 catalogue for the NGC 5044 group forms the basis of our target list for follow-up spectroscopy (see Section 2.2) and is 100% complete to \(B_T \sim 18\), and 90% complete to \(B_T \sim 19\). The luminosity function for the NGC 5044 group as determined by FS90 shows a steep faint-end slope, suggesting a significant number of dwarf galaxies and consistent with the high mass
2.1. Group selection and previous work

derived by [Brough et al., 2006a]. It is worth noting, however, that morphological
determinations of faint galaxies are difficult, and so the FS90 catalogue is likely to
contain a disproportionate number of background contaminants at low luminosities.
In their work, FS91 show that the early-type dwarf to giant ratio (EDGR) corre-
lates nearly monotonically with richness and that NGC 5044 group is consistent with
other groups and clusters in this regard.

A morphological re-classification of \( \sim 30 \) dwarf galaxies in the FS90 NGC 5044
group catalogue was carried out by [Cellone and Buzzoni, 2005] using deep imag-
ing from the ESO 3.6m telescope. In addition to their imaging, Cellone and Buzzoni
(2005) provide new spectroscopic recession velocity measurements for 13 low-
luminosity galaxies in the group which, combined with available literature recession
velocities, allowed them to undertake a kinematic study of the group’s galaxy pop-
ulation, albeit with a small sample. Their results show no strong evidence for
kinematic segregation between giant and dwarf group members, as is observed in
some clusters e.g. Virgo [Binggeli et al., 1993].

Surveys for neutral hydrogen in the group have been carried out using the Parkes
radio telescope and Australian Telescope Compact Array (ATCA) as part of GEMS,
and detect 22 HI sources within a 30 deg\(^2\) box centred on NGC 5044 (Kilborn et al. in
preparation; McKay et al., 2004). In Kilborn et al.’s work, late-type galaxies in
the NGC 5044 group show no clear evidence for a loss of HI gas, or ‘HI deficit’,
frequently associated with spiral galaxies in high-density environments (e.g. Solanes
et al., 2001). Additional, higher sensitivity HI observations for six NGC 5044 group
galaxies have been carried out using the Giant Metrewave Radio Telescope (GMRT)
by [Sengupta et al., 2007]. Of the six galaxies targeted by Sengupta et al., three
late-type spiral galaxies show evidence for a moderate HI deficiency and truncated
gas disks, consistent with gas being removed through interactions with the hot
intragroup medium, while a fourth S0 galaxy contains an abnormally large HI mass
of \( 8 \times 10^9 \) M\(_\odot\).

The majority of literature related to the NGC 5044 group concerns its X-ray
properties, owing to its high X-ray luminosity \( (L_X \sim 10^{43} \text{ erg s}^{-1}) \). X-ray observa-
tions and analyses of the group have been carried out using the ROSAT, Chandra,
XMM–Newton and Suzaku X-ray satellites (David et al., 1994; Buote et al., 2003,
2004; Tamura et al., 2003; Osmond and Ponman, 2004; Betoya-Nonesa et al., 2006;
These authors have found the group to have a cool-core component of $\sim 0.7$ keV within 10 kpc (consistent with the kinetic temperature of stars in NGC 5044 itself), and a warmer $\sim 1.4$ keV component outside of 40 kpc (characteristic of the group halo). The large radial extent of X-ray emission ($r > 60$ kpc) and high $L_X/L_B$ ratio ($\log L_X/L_B = 31.82 \pm 0.01 \text{ ergs s}^{-1} L_\odot^{-1}$; Osmond and Ponman, 2004) are key indications that the hot gas is associated with a group sized potential rather than just NGC 5044 itself. The wealth of different X-ray observations has provided a number of mass estimates for the group, which span a range from $\sim 1 - 7 \times 10^{13} \text{ M}_\odot$, although they are generally consistent with one another and dynamical estimates of the group’s total mass (based on galaxy kinematics).

Chemical abundances of the intragroup medium (IGM) in NGC 5044 have also been determined from X-ray observations, including iron (Tamura et al., 2003; Buote et al., 2004; Rasmussen and Ponman, 2007), silicon (Rasmussen and Ponman, 2007) and oxygen (Tamura et al., 2003). The chemical properties of NGC 5044’s IGM are consistent with other groups and clusters in exhibiting an iron “excess” in the central regions, generally attributed to enriched outflows from the central galaxy (e.g. Böhringer et al., 2004), however recent work has shown that a significant fraction of IGM metals may also originate from the central galaxy’s diffuse stellar halo or intra-group/intracluster stars (Sivanandam et al., 2009). $\alpha$-element abundances, traced by either oxygen or silicon, show a central excess similar to that of iron. In the outer regions, however, silicon abundances rise sharply (Rasmussen and Ponman, 2007), a feature also observed in other groups and clusters (Finoguenov et al., 2000; Rasmussen and Ponman, 2007).

Detailed X-ray observations focused on NGC 5044 identify the presence of X-ray cavities to the South-east and North-west of the central galaxy (Betoya-Nonesa et al., 2006; Gastaldello et al., 2009), which are likely to have been evacuated by known AGN activity (Rickes et al., 2004; Brough et al., 2007). Further support for this picture has come through detection of 8$\mu$m and 70$\mu$m dust emission in Spitzer observations (Temi et al., 2007), which show an extended structure coincident with the X-ray cavities and H$\alpha$ observations of the galaxy (Caon et al., 2000; Gastaldello et al., 2009) and hint towards active outflows from the core of NGC 5044.

In summary, literature data of the NGC 5044 group provides a multi-wavelength
look at its properties through a combination of X-ray, optical, IR and radio observations. The number of spectrally-confirmed (i.e. velocity confirmed) members is 35, although imaging studies suggest that significant numbers of low-luminosity galaxies not present in these spectroscopic studies are also likely group members. The group’s mass is determined to be $\sim 7 \times 10^{13} M_\odot$ from application of the virial theorem to confirmed group members and is consistent with X-ray observations, the scale of which suggest that the X-rays detected in the NGC 5044 group are likely associated with the group potential rather than just that of the central galaxy. HI observations provide only limited detection of galaxies in the NGC 5044 group, owing largely to the predominance of early-type morphologies in its galaxy distribution. Focusing more closely on the group’s brightest group galaxy (BGG), NGC 5044, the galaxy shows clear signs of outflows in X-ray imaging, optical emission-line analyses and IR imaging. Optical emission-lines ratios identify NGC 5044 as a LINER, most likely the result of an AGN at the galaxy’s centre.

For the remainder of this thesis we assume $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ where applicable and galaxy recession velocities are quoted as $cz$.

2.2 Data

In the previous Section we have described literature studies of the NGC 5044 group. In what follows we describe the data sample used for the remainder of this thesis, comprised of new spectral observations, published spectra and available redshift data for galaxies in the region surrounding NGC 5044.

2.2.1 Spectroscopic data

AAOmega Observations

We have obtained new spectra of NGC 5044 group galaxies using the AAOmega dual-beam bench mounted spectrograph on the 3.9m Anglo-Australian Telescope (AAT) in Siding Spring, Australia. AAOmega is fed by the 2dF multi-object top end which provides $\sim 400$ fibres covering a 2 deg diameter field. The large, $\sim 3 \text{ deg}^2$, field-of-view provided by 2dF allowed observation of the 162 objects in the FS90 NGC 5044 group catalogue (discussed in Section 2.1) simultaneously. The 5700 Å dichroic was
used in conjunction with the medium resolution 580V and 385R gratings, yielding FWHM dispersions of 3.5 Å and 5.3 Å for blue (λλ3700 – 5700 Å) and red (λλ5700 – 8800 Å) spectra respectively. The large wavelength coverage afforded by the dual-beam design of AAOmega provides spectra which cover all 25 Lick indices, [OII] and Hα.

Given the wide range of magnitudes spanned by targets in the FS90 catalogue, −19.3 ≤ MB ≤ −12.3, galaxies were separated into high- and low-luminosity sub-samples and observed separately in order to limit the effects of scattered light from the brightest targets. Observations were carried out 30 minutes at a time with a total of 3 to 4 observations per plate configuration. In each configuration an additional 30 – 35 “empty” fibres were assigned to be used for sky subtraction. To limit the effects of several wide defects in the blue arm CCD of AAOmega on the final coadded spectra, the central observing wavelength was shifted by 100 Å each night, ensuring that at any given wavelength usable data were obtained from at least 2 out of 3 nights. In total 4 and 17 hours of observations for high- and low-luminosity galaxies respectively were obtained. Details of observations are shown in Table 2.1. Seeing conditions across the three nights of observation varied from 1.0′′ to 1.8′′ with a median seeing of ∼1.3′′. Cloud cover across the three nights was minimal, and high cloud only effected observations at the end of night two (26 March) and beginning of night three (27 March).

Data reductions were carried out using a combination of IRAF routines and the 2DFDR reduction software supplied and maintained by the Anglo-Australian Observatory. First, bad pixel columns in individual observations were manually identified and repaired. The 2DFDR routine was then used to carry out the identification of fibre apertures, flat-fielding and throughput calibration, subtraction of the throughput corrected average sky frame and coaddition of final science spectra. The final coaddition of science frames was carried out after excluding any single exposures with very low flux relative to the other frames.
2.2. Data

The 6dF Galaxy Survey

The 6dF Galaxy Survey (6dFGS DR2; Jones et al., 2004) is a large, 17046 deg$^2$ survey of the Southern sky carried out using the Six-Degree Field (6dF) multi-object spectrograph on the UK Schmidt Telescope. 6dFGS targets were selected from the 2MASS Extended Source Catalogue (2MASS XSC; Jarrett et al. 2000), 2MASS and SuperCOSMOS to include all galaxies brighter than $K_{\text{tot}} = 12.75$ mag with wavelength coverage from $\lambda\lambda 4000 – 8400 \, \text{Å}$ at a resolution of $\sim 5.3 \, \text{Å}$ (FWHM).

In our list of potential NGC 5044 group members we include all 6dFGS galaxies within $4^\circ$ of NGC 5044 ($\sim 2$ Mpc in projected separation) and recession velocities between 500 and 5000 km s$^{-1}$, yielding 24 galaxies.

In the most recent release of the 6dFGS (DR2) the region surrounding NGC 5044 has not been surveyed completely, so 6dFGS galaxies included here are not uniformly distributed around NGC 5044. In particular, galaxies with declinations greater than $\sim -15.25^\circ$ ($\sim 0.65$ Mpc north of the group centre) are not present in the 6dFGS DR2 sample (see Fig. 2.1 for a more detailed footprint of 6dFGS coverage in this region).

Recession velocity and velocity dispersion measurements

Recession velocities and velocity dispersions for AAOmega and 6dFGS spectra were fit simultaneously using the penalised pixel-fitting (pPXF) software discussed in Cappellari and Emsellem (2004). Parameters derived using pixel-fitting methods are notoriously sensitive to the templates used to derive them. It is therefore important to minimise any bias related to so-called template mismatch on derived kinematics. The pPXF code is an extension of the Gauss-Hermite fitting method of van der Marel and Franx (1993) which allows for spectra to be fit using a linear combination of template spectra, all but eliminating errors in kinematic measurements induced by poorly matched template spectra.

As our input templates we use 50 stellar spectra from the MILES standard star library (Sánchez-Blázquez et al., 2006) spanning a broad range of spectral types. The particular choice of stars used to construct templates has only a minimal effect on the results derived using pPXF as long as they span a similar range of spectral types. We have investigated this briefly by fitting a sub-sample of our galaxy data...
Table 2.1: Details of AAOmega Observations

<table>
<thead>
<tr>
<th>Target</th>
<th>2dF Plate</th>
<th>Exp. (s)</th>
<th>Target</th>
<th>2dF Plate</th>
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<td></td>
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<tr>
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<td>HR 2429...</td>
<td>Plate 1</td>
<td>1s</td>
</tr>
<tr>
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<td></td>
<td>30s</td>
<td>HR 2574...</td>
<td>Plate 1</td>
<td>1s</td>
</tr>
<tr>
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<td>10s</td>
<td>HR 2701...</td>
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<td>1s</td>
</tr>
<tr>
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<td>HR 2701...</td>
<td>Plate 1</td>
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</tr>
<tr>
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<td>300s</td>
<td>HR 2970...</td>
<td>Plate 1</td>
<td>1s</td>
</tr>
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<tr>
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<tr>
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<td>HR 2574...</td>
<td>Plate 1</td>
<td>1s</td>
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<tr>
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<tr>
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<td>1200s</td>
<td>HR 3994...</td>
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<tr>
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</tr>
<tr>
<td></td>
<td></td>
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<td>1800s</td>
</tr>
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<tr>
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<tr>
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<tr>
<td>Galaxies (B_T ≥ 15)...</td>
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<td>1800s</td>
<td>Galaxies (B_T ≥ 15)...</td>
<td>Plate 0</td>
<td>1800s</td>
</tr>
</tbody>
</table>

Notes – Galaxies (B_T < 15) and Galaxies (B_T ≥ 15) represent observations of the high- and low-luminosity sub-samples described in Section 2.2.1 respectively. Observations were terminated early due to cloud cover.
Figure 2.1: Comparison of survey coverage for new AAOmega spectral observations (Section 2.2.1), 6dFGS galaxies (Section 2.2.1) and K08 (Section 2.2.2).
with sets of 50 randomly chosen stars from the MILES library and find typical deviations of $\sim 4 - 5$ km s$^{-1}$ in velocity dispersion.

In order for pPXF to provide meaningful velocity dispersion outputs we need to account for the difference in instrumental dispersion between our AAOmega spectra and the MILES stellar library. Overlap between the Lick and MILES stellar libraries is significant, so we have used the Lick standard stars observed throughout our AAOmega observing run to effectively measure the wavelength dependent broadening offset between AAOmega and the MILES library. In total we use 5 Lick/MILES stars to measure the median broadening difference. We find that scatter in our broadening measurements is significant for wavelengths below 4700 Å, however above this wavelength the dispersion offset is relatively stable at $\sim 57.7$ km s$^{-1}$ (2.3 Å FWHM). Adding in quadrature the spectral resolution of the MILES library, 2.3 Å, gives an average spectral resolution for AAOmega between 4700 Å and 5400 Å of 3.2 Å FWHM. This derived resolution is consistent with that found by Smith et al. (2007) for spectra taken using the 580V grating on AAOmega.

Standard star observations for the 16 6dFGS galaxies that we define as group members are unavailable, however we can measure the broadening offset between AAOmega and 6dF using the 8 galaxies present in both samples. In the $\lambda\lambda$4700 – 5400 Å wavelength range we find a mean offset between AAOmega and 6dF spectra of 103.6 km s$^{-1}$ (4.1 Å FWHM). Adding in quadrature the previously measured offset between AAOmega and the MILES library in this spectral region we adopt a total broadening of 118.6 km s$^{-1}$ (4.7 Å FWHM). The difference in aperture size between the 6dF and AAOmega fibres (6.7′′ vs. 2.1′′) will result in an additional broadening difference between the two galaxy spectra, independent of instrument resolution, of order 5 percent (Jorgensen et al., 1995). We do not take this aperture effect into account when calculating our broadening as the statistical nature of the Jorgensen et al. (1995) correction will likely only serve to introduce scatter in our relatively small number of galaxies, particularly given our broad range of galaxy types.

Prior to measuring kinematics using pPXF, MILES template spectra are smoothed to the AAOmega and 6dFGS resolution using the measured broadening offsets. The pPXF code allows for a penalty to be applied to the higher order terms of the Gauss-Hermite polynomials and here we adopt a moderately high bias of 0.8
Figure 2.2: Comparison of recession velocities measured in this work with available data from NED. Only the 29 overlapping galaxies with measured recession velocities \( \leq 4000 \, \text{km s}^{-1} \) are shown. The error bar in the upper left side of the figure represents our adopted systematic uncertainty of 50.7 km s\(^{-1}\).

Throughout fitting in order to limit spurious results from under-sampled or low S/N data. Random errors on our kinematic measurements are then calculated using a series of Monte Carlo simulations spanning a range of velocity dispersions and S/N. The scatter in our determination of instrumental broadening discussed above adds an additional, systematic uncertainty to our velocity dispersion measurements of 22 km s\(^{-1}\) and 41 km s\(^{-1}\) for AAOmega and 6dFGS galaxies respectively, which we include in quadrature.

Fig. 2.2 shows the relationship between newly measured redshifts and those available in the NASA/IPAC Extragalactic Database (NED), showing the velocity difference between the two plotted against our measured velocities. Velocities are shown only for those galaxies for which we find recession velocities \( \leq 4000 \, \text{km s}^{-1} \) (the range of interest for possible NGC 5044 group members), however background objects with higher velocities show similar good agreement with the literature. We find no evidence for systematic variations with recession velocity out to a redshift of \( \sim 0.7 \) (our highest redshift object), however based on the median absolute deviation between our velocity measurements and those in NED we adopt a systematic uncertainty of 50.7 km s\(^{-1}\).
Chapter 2. The NGC 5044 group and data

2.2.2 Literature velocity data

NASA/IPAC Extragalactic Database

Given the centrally concentrated nature of our AAOmega observations and the incomplete spatial coverage available from the 6dFGS DR2 data, we have supplemented our combined AAOmega and 6dFGS galaxy list using sources with known recession velocities from the NED in the same position and velocity range, providing 51 additional galaxies to our sample. The heterogeneous nature of the NED data means that an accurate estimate of incompleteness effects is difficult. However, Brough et al. (2006b) have shown NED to be complete in recession velocity and photometry to $K < 11$ mag, with statistically similar results obtained when fainter magnitude objects are included.
2.2. Data

Figure 2.4: Photometric comparison between $K$-band magnitudes from 2MASS and DENIS (as measured by P05). Error bars represent 1σ deviations. The solid line represents equality, while the dashed line represents a least squares fit to the data.

Kilborn et al. (2008) HI observations

As discussed in Section 2.1, the NGC 5044 group has been surveyed for neutral hydrogen as part of the GEMS project using the 20-cm multi-beam receiver on the Parkes radio telescope by Klborn et al. (in preparation, hereafter K08; see also McKay et al., 2004). They surveyed a $5.5^\circ \times 5.5^\circ$ region centred roughly on NGC 5044 and identified 23 HI detections above a mass limit of $1.8 \times 10^8 M_\odot$ (flux levels above 18 mJy beam$^{-1}$). Of these, 5 represent new galaxy detections which have been confirmed using high resolution imaging from the ATCA (further details will be given in K08), and so these new galaxies are included in our velocity sample.

2.2.3 Photometric Data

In order to supply a cross-reference for the $B$-band magnitudes of FS90, as well as supplementary $B$-band photometry for galaxies not in the FS90 galaxy list (i.e. those selected from 6dFGS, K08 and NED) we have adopted additional $B$-band photomet-
ric data from Paturel et al. (2000, hereafter P00). They obtain $B_T$ from Digitised Sky Survey (DSS) plates and provide total $B$-band magnitudes for 65 of the 162 galaxies in the FS90 NGC 5044 group sample, 21 out of 24 of our 6dFGS selected galaxies, 36 of the 51 NED galaxies, and 1 out of 5 from the K08 sample.

In Fig. 2.3 we show a comparison of FS90 and P00 total $B$-band magnitudes, showing the good agreement of the two $B_T$ determinations. There is no evidence for any systematic offsets between the two samples. The rms scatters about the one-to-one and best fit lines are 0.38 and 0.37 mags respectively, and we therefore adopt the P00 magnitudes without additional correction when FS90 measurements are unavailable.

K-band magnitudes provide a reasonable proxy for stellar mass as they are relatively unaffected by dust extinction and young, hot stars. We have therefore compiled the available $K$-band photometry of our sample. The Two Micron All Sky Survey (2MASS, Skrutskie et al., 2006) has provided an excellent resource of $K$-band photometry for a large number of galaxies, and supplies total $K$-band magnitudes and isophotal radii ($r_{K20}$) for 41 of the 162 galaxies in the FS90 target list and all 24 6dFGS selected galaxies.

To provide greater $K$-band coverage, we adopt additional magnitudes from the Deep Near Infrared Survey (DENIS; Paturel et al., 2005, hereafter P05). In Fig. 2.4 we show a comparison of 2MASS and P05 $K$-band magnitudes. The agreement between the two samples is good and there are no suggestions of systematic offsets. We preferentially use 2MASS $K$-band magnitudes, supplementing with P05 data where necessary.

In total, the combined AAOmega, 6dFGS, GEMS HI and NED data provide 152 galaxies with redshifts between 500 and 5000 km s$^{-1}$ in the region of NGC 5044.
Galaxy dynamics in the NGC 5044 group

Galaxy dynamics provide a powerful tracer of group evolution. After initial violent relaxation where galaxies are dominated by a collective potential (Lynden-Bell, 1967), the dynamics of group and cluster galaxies are predominantly affected on more local scales. Of the several possible mechanisms driving galaxy evolution, those dependent on the size of the potential well (e.g. harassment; Moore et al., 1996) or density of the intra-cluster medium (e.g. ram-pressure stripping; Gunn and Gott, 1972) will be most effective in clusters. Conversely, the low-velocity group environment favours mergers as the preferred method of relaxation due to the growing efficiency of dynamical friction at low relative velocities.

It has been shown that mergers can lead to both morphology and luminosity segregation (Yepes et al., 1991; Fusco-Femiano and Menci, 1998), and observations suggest that galaxies are segregated in both groups (Mahdavi and Geller, 2001; Girardi et al., 2003) and clusters (Adami et al., 1998; Biviano et al., 2002; Lares et al., 2004). Since mergers will also affect the relative number of galaxies at a given luminosity, one might expect the prevalence of mergers in groups to influence the shape of the group luminosity function. This is, in fact, a possible explanation of the commonly observed “dip”, indicative of intermediate mass galaxies merging to form more luminous ones (e.g. Trentham and Tully, 2002; Miles et al., 2004). It is also worth noting that recent observations of ram-pressure stripping in groups (e.g. Bureau and Carignan, 2002; Kantharia et al., 2003; Rasmussen et al., 2006) support the results of numerical simulations which suggest that group-level ram-pressure stripping could also play some role in group galaxy evolution (Hester, 2006).

Typical studies of poor groups may classify 10 – 20 galaxies as group members,
Chapter 3. Galaxy dynamics in the NGC 5044 group

the majority of which have had their membership assigned using photometric or morphological criteria. More robust studies have included only galaxies for which recession velocity measurements are available (e.g. Zabludoff and Mulchaey, 1998; Carlberg et al., 2001; Brough et al., 2006a), however this often leads to the need to stack groups in order to measure their properties due to the low numbers of redshifts typically available. The problem with stacking groups, however, is that while it is then possible to constrain the generalised global properties of groups (e.g. mass distribution, velocity dispersion profile etc.) the individual properties of any single group are washed out.

In this thesis our large sample of NGC 5044 group galaxies allows us to undertake a detailed dynamical analysis of the group using only those galaxies which are spectroscopically confirmed members and without the need to stack multiple groups together. In this Chapter we describe the determination of group membership using the list of potential members described in Chapter 2. We then go on to derive the general dynamical properties of the group and assess its current apparent dynamical state, providing a backdrop for the stellar population analyses undertaken in later Chapters. In this Chapter we follow a labelling convention such that $R$ denotes 2D, projected radii and $r$ indicates 3D, deprojected radii.

### 3.1 Group membership

The new AAOmega observations described in Chapter 2 provide a significantly increased spectroscopic sample with which to define the NGC 5044 group. Here we use the combined sample of AAOmega, 6dFGS, NED and K08 (see Section 2.2) to reassess NGC 5044 group membership.

Brough et al. (2006a, hereafter B06) used data from NED and 6dFGS to define the NGC 5044 group using a friends-of-friends algorithm (FoF; Huchra and Geller, 1982) which selects group members down to a specified density contrast, in the case of Brough et al. $\delta = 150 \rho_0$, where $\rho_0$ is the critical density. Groups derived using the FoF method are sensitive to the maximum allowed projected and velocity separation (i.e. the linking length and velocity), the luminosity function and the magnitude limit of the sample. The inhomogeneous nature of our combined sample means that no single luminosity function or magnitude limit will be adequate for
3.1. Group membership

Figure 3.1: Galaxy recession velocities against their projected distance from NGC 5044. Circles and crosses represent galaxies included and excluded from the group respectively. The vertical dashed line shows a radial cut of 1.6 Mpc, beyond which galaxies are no longer considered as members. Dotted lines represent the $3\sigma$ velocity limit of the data, with the solid line showing the moving mean velocity.

Selection of the group using an FoF algorithm, and we therefore adopt a clipping method as it requires no a priori assumptions regarding our data.

Membership of the NGC 5044 group is assigned using an iterated velocity dispersion clipping as follows. Galaxies are binned radially, using NGC 5044 as the centre, and a moving mean velocity and velocity dispersion $\sigma$ are calculated. Galaxies with velocities greater than $3\sigma$ from the moving mean are removed from the group member list and the process is repeated until no additional galaxies are removed.

Velocity clipping is particularly well suited to this sample as the NGC 5044 group is well separated in velocity space from background contamination, illustrated in Fig. 3.1. We have imposed a cut at 1.6 Mpc in projected radius, beyond which our moving velocity dispersion begins to rise due to increasing velocity outliers. It is likely that some of the galaxies beyond this cut are also group members, however beyond 1.6 Mpc we are unable to reliably separate genuine group members from unassociated galaxies and so no longer include these galaxies as group members. We note that the inclusion or exclusion of galaxies in this region has a negligible
Figure 3.2: Distribution of confirmed group members on the sky. Filled circles, open circles and spirals represent elliptical, S0 and late-type galaxies respectively. Crosses mark group members with unknown morphological types.

The member list for the NGC 5044 group is shown in Table 3.1 and includes 111 galaxies, including 71 from FS90, 16 from 6dFGS, 19 from NED and 5 from K08. In Fig. 3.2 we show the distribution of our confirmed group member galaxies on the sky, with symbols representing different morphological types.

The group properties we find using velocity clipping rather than FoF are consistent within uncertainties with those from B06.
Table 3.1: Velocity confirmed members of the NGC 5044 group. Columns are as follows: (1) Galaxy Identifier (2) Right ascension (J2000), (3) Declination (J2000), (4) Recession Velocity, (5) FS90 membership classification, where 1, 2 and 3 represent definite, likely and possible members respectively, (6) B-band magnitude, (7) K-band magnitude and error, (8) Morphological type. For FS90 galaxies we adopt their morphological classification, except where morphologies have been modified by Cellone and Buzzoni (2005, marked with a). For all other galaxies morphologies are adopted from NED.

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<tr>
<th>Galaxy I.D.</th>
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<th>DEC (J2000)</th>
<th>cz (km s(^{-1}))</th>
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<th>BT</th>
<th>KT</th>
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Table 3.1 – Continued

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Chapter 3. Galaxy dynamics in the NGC 5044 group

Figure 3.3: $B$-band luminosity function for the NGC 5044 group. Open circles represent the luminosity function of the FS90 sample, while filled circles represent our spectroscopically confirmed group member sample. Open squares show the results of including additional galaxies from the FS90 sample based on their likelihood of group membership (see Section 3.1.1). Galaxies are binned at 0.5 magnitude intervals and Poisson errors are shown. Note that points may overlap.

3.1.1 Comparison with FS90

FS90 used morphological criteria to arrive at their original membership classification (e.g. low-luminosity spiral galaxies are likely to be background objects). Since we have obtained recession velocities for 103 of their 162 NGC 5044 group galaxies we are able to re-evaluate their original group membership. FS90 organised their observations into three different membership classes designated 1 (definite members), 2 (likely members) and 3 (possible members).

Our spectroscopic sample includes 60, 14 and 29 class 1, 2 and 3 galaxies respectively. Confirmed NGC 5044 group members and their FS90 classifications are shown in Table 3.1. Non-members, their velocities and FS90 classifications are given in Table 3.2. Of class 1 galaxies we find 55 of the 60 to be genuine group members, $\sim 92$ percent, indicating that class 1 galaxies in the FS90 catalogue are generally reliable group member galaxies. The fractions of genuine group member class 2 and 3 galaxies fall, as one might expect based on their increasing uncertainty in group membership, and we confirm 7 class 2 and 9 class 3 galaxies as bona fide group members (50 and $\sim 31$ percent respectively). We note that the NGC 5044 group is the...
most distant considered by FS90, and so it is perhaps not surprising that the classification of galaxies is somewhat unreliable given the difficulty in morphologically classifying faint galaxies.

Fig. 3.3 shows a comparison of the $B$-band luminosity functions (LF) between our confirmed group sample and the complete FS90 sample. The largest difference between the two comes at faint magnitudes where our spectral observations become significantly incomplete and FS90 likely includes a significant number of faint class 3 membership galaxies, of which our observations suggest only one-third are actually group members.

We adopt a Monte Carlo approach to correct the LFs shown in Fig. 3.3 for our own incompleteness and contamination present in the FS90 sample. Confirmed group member galaxies are always included in the analysis, however there are 59 dwarf galaxies in the FS90 sample with no recession velocity information. We therefore sample these remaining FS90 dwarf galaxies based on the fractions of class 1, 2 and 3 included in our confirmed group sample (i.e. 92, 50 and 31 percent of each respective membership class are included in the Monte Carlo group each iteration). This provides a more accurate estimate of the luminosity function and allows us to examine the effect of contamination on the FS90 sample.

Fig. 3.3 shows that our spectroscopic sample is in excellent agreement with the FS90 sample for $M_B < -15$, where the FS90 sample is greater than 90 percent complete, and implies a flat luminosity function. In the region $-15 < M_B < -14$ our spectroscopic sample begins to deviate from the FS90 sample, however our Monte Carlo corrections show that the majority of this is due to the inclusion of outliers in the FS90 sample, rather than incompleteness in our data. Below $M_B > -14$ the LF shows tentative evidence for an upturn, however our sample is significantly incomplete in this magnitude range so we abstain from drawing any further conclusions.

### 3.2 Dynamical formulae

In the remainder of this Chapter we will discuss the dynamical properties of the NGC5044 group as derived from our confirmed group members. Before doing so, here we quickly step through the dynamical formulae used to derive these quantities.

Velocity dispersions are calculated using the biweight scale estimator (Beers
### Table 3.2: Confirmed non-members and possible stars from the FS90 NGC 5044 Catalogue

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<td>052</td>
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<td>061</td>
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Notes. Columns are as follows: (1) FS90 galaxy identifier, (2) Right ascension, (3) Declination, (4) Measured recession velocity, (5) FS90 membership classification, where 1, 2, and 3 represent definite, likely and possible members respectively.
3.2. Dynamical formulae

\[ \sigma_v = n^{1/2} \left[ \frac{\sum_{|u_i| < 1} (v_i - \bar{v})^2 (1 - u_i^2)^4}{\sum_{|u_i| < 1} (1 - u_i^2)(1 - 5u_i^2)} \right]^{1/2}, \]  
\hspace{1cm} (3.1)

where \( v_i \) denotes the recession velocity of the \( i^{th} \) galaxy and \( \bar{v} \) is the median group velocity. \( u_i \) is then defined as

\[ u_i = \frac{(v_i - \bar{v})}{c \text{MAD}}, \]  
\hspace{1cm} (3.2)

with \( \text{MAD} \) being the median absolute deviation (median deviation of the sample with respect to the sample median). Where we calculate the velocity dispersion for low numbers of galaxies (< 15), we use the gapper algorithm of Beers et al. (1990),

\[ \sigma_v = \sqrt{\frac{\pi}{n(n-1)}} \sum_{i=1}^{n} w_i g_i, \]  
\hspace{1cm} (3.3)

where \( w_i = i(n-i) \) and \( g_i = z_{i+1} - z_i \). This has been shown to be more efficient for low sample sizes than the biweight estimator (Beers et al., 1990).

Virial mass, \( M_V \), has been calculated using the virial mass estimator from Heisler et al. (1985)

\[ M_V = \frac{3\pi N}{2G} \sum_{i<j} \frac{v_{i,gc}^2}{1/R_{gc,ij}}, \]  
\hspace{1cm} (3.4)

where \( v_{i,gc} \) is the velocity of galaxy \( i \) with respect to the group centroid and \( R_{gc,ij} \) is the projected group-centric separation from other galaxies.

The \( R_{500} \) radius has been calculated using the velocity dispersion via

\[ r_{500} = \frac{0.096\sigma_v}{H_0}. \]  
\hspace{1cm} (3.5)

The crossing time is defined as

\[ t_c = \frac{3r_H}{5^{3/2}\sigma_v}, \]  
\hspace{1cm} (3.6)

in units of \( H_0^{-1} \). \( r_H \) is the mean harmonic radius (Ramella et al., 1989) given by
Chapter 3. Galaxy dynamics in the NGC 5044 group

\[ r_H = \pi D \sin \left[ \frac{1}{2} \frac{n(n - 1)}{2} \sum_i \sum_{j>i} \frac{\theta_{ij}^{-1}}{2} \right], \]  

(3.7)

where \( D \) represents the distance to the group and \( \theta_{ij} \) is the projected angular separation between galaxies \( i \) and \( j \).

3.3 Global properties

A vital step in establishing the role that groups play in the evolution of galaxies is establishing their place between clusters and the field. Are groups simply low-mass clusters, or do their member galaxies exhibit unique signs of formation and evolution? In order to assess this we first need to establish the relation of the NGC 5044 group to other groups and clusters.

The dynamical properties of the NGC 5044 group are summarised in Table 3.3, which shows the mean velocity, velocity dispersion, \( R_{500} \) radius, dynamical mass and crossing time we derive using the formulae in Section 3.2. For comparison, we also show similar measurements from the literature.

While we have more than tripled the number of group members included relative to previous studies, our results for the mean velocity, velocity dispersion, \( R_{500} \) radius, mass and crossing time are all consistent with previous estimates within errors. We find the group to be massive, nearly \( 10^{14} \) M\(_{\odot} \) in total mass, which combined with the short crossing time leads us to the same conclusions of B06 that the NGC 5044 group is a classically massive, dynamically mature group.

3.3.1 Dynamical state

Addressing the dynamical state of the NGC 5044 group is key in our goal of establishing its evolutionary history. In particular, the brightest group galaxy (NGC 5044) is known to have a peculiar velocity of \( \sim 150 \) km s\(^{-1} \) with respect to the mean group velocity (Cellone and Buzzoni 2005; B06), which could be indicative of non-equilibrium due to recent mergers. The peculiar velocity found for NGC 5044, scaled by the group’s velocity dispersion, is 0.45\( \sigma_v \), and within the range typically found for

\[^{1}\text{The } R_{500} \text{ radius is defined as the radius at which the projected density reaches 500 times the critical density.}\]
3.3. Global properties

Table 3.3: NGC 5044 group dynamical properties compared with available literature values.

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<th>$\sigma_v$ ($\text{km s}^{-1}$)</th>
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<th>$M_V$ ($10^{13} \text{M}_\odot$)</th>
<th>$t_c$ ($H_0^{-1}$)</th>
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<td>...</td>
</tr>
<tr>
<td>Osmond and Ponman (2004)</td>
<td>18</td>
<td>2518±100</td>
<td>426±74</td>
<td>0.62±0.08</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Notes. Columns are as follows: (1) Source. (2) Number of group members included in the calculated values. (3) Mean recession velocity and $\sigma/\sqrt{N}$ error. (4) Velocity dispersion and $1\sigma$ error (when available). (5) $R_{500}$ radius. (6) Crossing time.

relaxed groups and clusters (e.g. Oegerle and Hill 2001; B06; Hwang and Lee 2008). Peculiar brightest group and cluster galaxy (BGG/BCG) velocities are therefore not in and of themselves indicative of groups out of dynamical equilibrium.

To further assess the dynamical state of the NGC 5044 group we examine both the characteristics of line-of-sight (LOS) velocities and dynamical measurements such as crossing time. Fig. 3.4 shows the LOS velocity distribution for our group sample with the best-fit Gauss-Hermite distribution overlayed. In fitting a fourth-order Gauss-Hermite expansion to our LOS velocities (e.g. Zabludoff et al., 1993) we find negligible values for the $h_3$ and $h_4$ coefficients, measurements of the distribution skewness and kurtosis. The normal distribution of LOS velocities suggests that the group is relaxed and well mixed, as $h_3$ and $h_4$ are generally indicative of substructure or strong orbital anisotropies in the group velocities (e.g. Merritt, 1988).

The crossing time of a group can also be used as an indication of a group’s virialization, where crossing times $> 0.09 H_0^{-1}$ are usually indicative of groups whose galaxy orbits have not had sufficient time to circularise in the group potential (Nolthenius and White, 1987). The short crossing time found for the NGC 5044 group ($t_c = 0.03 \pm 0.004 H_0^{-1}$, $\sim 0.4$ Gyr) therefore suggests that it is most likely virialised and consistent with the low kurtosis we find for the velocity distribution, discussed above.

The use of crossing time as an indicator of virialization can be somewhat questionable in groups, and studies examining very small groups ($N_{\text{gal}} \sim 5 – 10$) have found that using $t_c$ as the sole indicator of virialization can lead to the inclusion of up to 20 percent spurious associations (see e.g. Diaferio et al., 1993; Niemi et al., 2007). However this discrepancy is primarily a concern for galaxies which are only...
questionably bound. A comparison of the NGC 5044 group to the virial parameters discussed in Niemi et al. (2007) suggests that groups of order the NGC 5044 group mass are bound with greater than 99 percent probability and that the crossing time is a useful indicator in assessing dynamical status.

The availability of XMM X-ray observations for the NGC 5044 group (T. Ponman 2007, private communication) means that we have an additional and independent measure for the group centre of mass. Poole et al. (2006) have shown that offsets in the X-ray peak from the centroid of X-ray emission can be caused by sub-cluster mergers which cause the X-ray peak to “slosh” with respect to the centroid. The measurement of such an offset is therefore a strong indicator of group or cluster merger activity and dynamical state. Using an XMM mosaic, we calculate the peak–centroid displacement for the NGC 5044 group, finding a nominal offset of $\sim 0.003 R_{500}$, which is within the range of relaxed clusters in the Poole et al. (2006) simulations. We do note, however, that this test is sensitive only to offsets in the plane of the sky, and so we are unable to rule out significant displacements of the X-ray peak along the line of sight.

From the above indicators we therefore conclude that the NGC 5044 group is in equilibrium and virialized.
3.3.2 Substructure

Based on the paradigm of hierarchical structure formation, conglomerations of galaxies such as clusters and large groups are formed via the successive infall of smaller structures. Substructures are found in anywhere from 30 to 70 percent of optically observed clusters (Girardi et al., 1997; West et al., 1988; Burgett et al., 2004; Ramella et al., 2007), providing considerable evidence in support of this merging scenario. While the NGC 5044 group is considerably smaller than rich clusters typically analysed we still expect it to have evolved via similar hierarchical mechanisms, and so a search for dynamical substructures is relevant.

Here we adopt the Dressler-Shectman $\Delta$ statistic (Dressler and Shectman, 1988) as a means for measuring the three-dimensional (space-velocity) substructure present in our sample. This statistic, while originally used for measurement of substructure in clusters, has been shown to be effective at identifying dynamical substructures even at smaller, group scales (Pinkney et al., 1996).

Calculation of the $\Delta$ statistic involves the summation of local velocity anisotropy, $\delta$, for each galaxy in the group, defined as

$$\delta^2 = \left( \frac{N_{nn} + 1}{\sigma^2} \right) \left[ (\bar{v}_{\text{local}} - \bar{v}_{\text{group}})^2 - (\sigma_{\text{local}} - \sigma)^2 \right]$$ (3.8)

where $N_{nn}$ is the number of nearest neighbours over which the local recession velocity ($\bar{v}_{\text{local}}$) and velocity dispersion ($\sigma_{\text{local}}$) are calculated. Here we adopt $N_{nn} = \sqrt{N}$, following Pinkney et al. (1996). The test statistic $\Delta$ is larger for increasing levels of substructure in the group.

In order to provide a normalisation for this statistic, and therefore a means of measuring its significance, we perform 1000 Monte Carlo simulations of our data, randomly shuffling the velocities in the group and re-calculating the $\Delta$ statistic. This allows us to calculate the probability that our measured $\Delta$ can be obtained from a random distribution of recession velocities.

It is important to note that there are two insensitivities of the $\Delta$ statistic that must also be considered. The first is related to the $\Delta$ statistic’s inability to detect superimposed substructures, mentioned by Dressler and Shectman (1988). A second caveat is that the $\Delta$ statistic is insensitive to equal mass mergers occurring in the plane of the sky (i.e. similar mean velocity and dispersion), as discussed by Pinkney.
Figure 3.5: Bubble diagram for the Dressler-Shectman substructure test. Each circle represents a galaxy in the NGC 5044 group with sizes scaled by $e^\delta$ (see text). The left panel shows galaxies scaled by their observed $\delta$ while the centre and right panels show the maximal and median substructure results from our Monte Carlo simulations of the data. Orientation and area displayed in each panel are the same as in Fig. 3.2.

et al. (1996).

We find suggestions of substructure in the NGC 5044 group, with the group’s $\Delta$ value significant at greater than the 99.9 percent level. It is possible that high $\Delta$ values can be obtained via rotation or velocity gradients across the group. Based on this, we have examined our velocity data for any signs of rotation, however we find no evidence for bulk rotation with $v_{\text{rot}} \sim 53 \pm 49 \text{ km s}^{-1}$.

To visually search for merging sub-groups that could be responsible for the large $\Delta$ value, in Fig. 3.5 we show a bubble plot for the NGC 5044 group. Here, each galaxy is represented with a circle whose radius is scaled as $e^\delta$ (where $\delta$ is taken from Eqn. 3.8). As is evident from this figure, there is a significant sub-clump of galaxies in the north-east outskirts of the group, which is responsible for the high $\Delta$ value. Removing these galaxies and re-running the substructure test results in the group’s $\Delta$ value being significant at only the 70 percent level.

3.3.3 Number density profile

Hierarchical formation in the context of the ΛCDM paradigm makes particular statistical predictions regarding the shape of resulting density profiles. These predictions are primarily motivated by numerical simulations and suggest that halo profiles
Figure 3.6: Average projected number density as a function of projected radius. Open squares, filled circles and filled squares represent NED, AAOmega and 6dFGS data respectively. Data are scaled to match in number density at radii between 0.1 and 0.6 Mpc (see §3.3.3). Note that as a result of this scaling symbols overlap. The solid and dashed lines represent the best fit NFW and Hernquist profiles.

are well described by a combination of power laws growing progressively steeper with increasing radius (Dubinski and Carlberg, 1991; Navarro et al., 1995, 1996, 1997). Such exponential profiles have been found to be applicable across a range of groups and clusters (e.g. Carlberg et al., 1997a,b; Biviano and Girardi, 2003).

The average projected number density of galaxies, $\Sigma_N$, can be represented as a projection of the volume density $\nu(r)$ via an Abel integral where

$$\Sigma_N(R) = 2 \int_{R}^{\infty} \nu(r) \frac{r}{\sqrt{r^2 - R^2}} dr.$$  \hfill (3.9)

Here we adopt a general form of the volume density

$$\nu(r) = \frac{A}{r(r + a_v)^p},$$  \hfill (3.10)

where $a_v$ is the radius of the transition between the inner and outer profile slopes. Different outer slopes of the profiles are obtained for a fixed valued of $p$, and adopting $p = 2$ or 3 gives an NFW (Navarro et al., 1995, 1996, 1997) or Hernquist (Hernquist, 1990) profile respectively. In Fig. 3.6 we show the binned surface density profiles...
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calculated for each of the three data sets (either NED, 6dFGS or AAOmega), where the 6dFGS and AAOmega bins have been corrected for their known incomplete spatial coverage. As a rough correction to facilitate fitting a mean density profile we have scaled the data to match in density between 0.2 and 0.6 Mpc, applying the derived offset to the remaining bins.

The profiles fit to this corrected data are shown with the solid and dashed lines (NFW and Hernquist profiles) in Fig. 3.6, where bins containing a single galaxy have been excluded from the fitting process. Both fits are reasonable, however the NFW profile provides a statistically better fit. The scale radius for the best fit NFW profile is $a_v = 0.26 \pm 0.02$, consistent with the CNOC cluster profile fits of Carlberg et al. (1997a). For the remainder of relevant analyses we will consider only the best fit NFW profile.

3.3.4 Velocity dispersion profile

The underlying mass distribution of a group or cluster is related to the volume density and velocity dispersion profiles via the Jeans equations. By measuring the observed density and velocity distributions, one can infer properties of the group mass distribution. This analysis is often applied to group and cluster systems where galaxies can be treated as tracer particles, with the caveat that interpretation using the Jeans equations is only appropriate for systems in equilibrium.

The velocity dispersion profiles of clusters are generally found to be falling with radius (e.g. Carlberg et al., 1997a; Girardi et al., 1998; Biviano and Girardi, 2003; Biviano and Katgert, 2004) and indicative of centrally concentrated mass distributions. Group studies measuring velocity dispersion profiles are generally in good agreement, finding either falling or roughly flat profiles with radius (e.g. Zabludoff and Mulchaey, 1998, B06). However, there is some evidence that the velocity dispersion is actually smoothly rising with radius (Carlberg et al., 2001), suggesting that galaxies are concentrated with respect to the dark matter distribution due to contraction within the halo (e.g. by dynamical friction).

The velocity dispersion at a given radius is calculated here in a similar fashion to the number density, using the projection of the radial velocity dispersion and number density such that
3.3. Global properties

Figure 3.7: Velocity dispersion profile of the NGC 5044 group. NGC 5044 is assumed to be the centre of the group. Bins contain 10 galaxies each and 1σ jackknife errors are shown. Best fit profiles for $\beta = 1, \frac{1}{2}$ and 0 are overlayed (lines overlap).

$$\sigma_{p}^{2}(R) = \frac{1}{\Sigma_{N}(R)} \int_{R}^{\infty} \nu \sigma_{r}^{2} \left( 1 - \frac{\beta R^{2}}{r^{2}} \right) \frac{r}{\sqrt{r^{2} - R^{2}}} dr,$$

where $\beta = 1 - \frac{\sigma_{\theta}^{2}}{\sigma_{r}^{2}}$ is the velocity anisotropy parameter. We have adopted a simple form of the radial velocity dispersion used by Carlberg et al. (1997a) defined as

$$\sigma_{r}^{2}(r) = \frac{B}{b + r},$$

where $B$ and $b$ are free parameters in our fit.

In Fig. 3.7 we show the velocity dispersion profile derived for our data, with best fit velocity dispersion profiles for $\beta = 1, \frac{1}{2}$ and 0 (purely radial, marginally isotropic, and isotropic orbits). Bins contain 10 galaxies each and velocity dispersions have been calculated using the gapper algorithm (Beers et al. 1990; Eqn. 3.3). As expected for a relaxed group, we find the velocity dispersion falling with radius regardless of our allowed values of $\beta$, implying that the group mass is centrally concentrated and in agreement with the profile found by B06 for their stacked GEMS groups.

There is some suggestion of fluctuation in the velocity dispersion profile between 100 and 200 kpc (also seen in Fig. 3.1), however due to our relatively low numbers its significance is unclear. Fluctuations in the velocity dispersion profile are commonly observed in clusters (e.g. den Hartog and Katgert, 1996) and studies which allow
the orbital anisotropy parameter, $\beta$, to vary find that these fluctuating profiles can be reasonably fit by a varying orbital distribution with radius (see e.g. Biviano and Katgert, 2004; Hwang and Lee, 2008). These velocity dispersion variations can also be produced if there are multiple sub-populations in the group, either on uniquely different orbits (e.g. radial or tangential) or offset from the assumed centre of the group.

### 3.3.5 Mass estimates

Table 3.4 shows a comparison of mass estimates for the NGC 5044 group in the literature, derived both dynamically and from X-rays. As this table shows, there are a variety of estimates for the NGC 5044 group mass from $\sim 10^{13}$ to $10^{14} \, M_\odot$. Given this variation, and our attempt to compare the NGC 5044 group with other groups and clusters, we will briefly examine the reliability and consistency of these mass estimates.

For this comparison we have built a sample of groups and clusters using two separate data sets. The first is the 15 Southern GEMS groups studied by B06, which contains groups in the range $12.3 < \log M_\odot < 13.8$. B06 have calculated the dynamical properties of these groups (i.e. virial mass, radius etc.) and the X-ray properties of the groups have been presented by Osmond and Ponman (2004).

The second data set consists of 38 clusters from the Advanced Satellite for Cosmology and Astrophysics (ASCA) Cluster Catalogue of Horner (2001). The velocity dispersion and virial mass measurements for these clusters have been adopted from Girardi et al. (1998), and only those clusters with $> 30$ confirmed members are included in this analysis.

In order to compare the X-ray and dynamical masses for a number of sources, we first need normalise them to a standard mass scale. For dynamical masses this...
Figure 3.8: Comparison between dynamically and X-ray derived mass estimates for groups and clusters. Groups from B06 are shown with open triangles and circles, representing group and galaxy scale X-ray emission respectively. Open squares are Horner clusters with velocity dispersions measured by Girardi et al. (1998, see text for details). The solid line represents a one-to-one correlation, and the dashed line is a best fit to the data with a slope of $0.83 \pm 0.08$. Our measurements for NGC 5044 are shown as the large, filled triangle.
normalisation is not straight forward. Masses for the GEMS and ACC samples are both calculated as virial masses, which implies a density contrast of \(\delta_{\text{vir}} = 18\pi^2 \approx 178\) for an \(\Omega_0 = 1\) universe \(\text{(Bryan and Norman, 1998)}\). However there is no implicit radius assumption in these calculations, so scaling these masses to a different density contrast (e.g. \(\delta = 200\)) is difficult.

We calculate X-ray masses to a similar density contrast as the dynamical estimates. This has been done using the \(\beta\)-model fit parameters to calculate the group mass in terms of density contrast and X-ray temperature \(\text{(Horner et al., 1999)}\) such that

\[
M(\delta, \beta, T_X) = 1.1 \times 10^{15} \delta^{-1/2} \beta^{-3/2} \left(\frac{T_X}{\text{keV}}\right)^{3/2} \\
\times \left(1 - 0.01 \frac{\delta r_c^2}{\beta T_X}\right)^{3/2} h^{-1} M_\odot.
\]  
(3.13)

In this case, we adopt \(\delta = 178\) and use the \(\beta\)-model fits from \(\text{Osmond and Ponman (2004)}\) for the GEMS groups and \(\text{Fukazawa (1997)}\) for the ACC cluster sample.

In Fig. 3.8 we show the comparison of dynamical masses and re-calculated X-ray masses. This comparison shows a systematic offset between X-ray and dynamical masses, however the two estimates scale almost linearly. For the NGC 5044 group, the mass we calculate using Eqn. 3.13 is consistent with that of \(\text{Betoya-Nonesa et al. (2006)}\), i.e. \(\sim 5.1 \times 10^{13} M_\odot\), while our dynamical mass is consistent with the general group and cluster trend. So, while the dynamical and X-ray masses for this group disagree, their disagreement is consistent with the systematic offset present between the two methods used.

### 3.3.6 Group scaling relations

In self-similar models of group and cluster formation the amount of gas present in a halo is directly related to the depth of the potential well, leading to correlations of X-ray luminosity with both gas temperature and velocity dispersion. In this self-similar model the X-ray luminosity scales directly with velocity dispersion as \(L_X \propto \sigma_v^4\). At cluster masses there is general agreement that observations are consistent with the self-similar picture, with numerous studies finding power law slopes consistent with
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Figure 3.9: X-ray luminosity variation ($L_X(R_{500})$) with velocity dispersion ($\sigma_v$) in groups and clusters. Group and galaxy scale emission from B06 groups are shown using triangles and circles respectively. X-ray undetected groups are shown as upper limits. Open squares are Horner clusters with velocity dispersions measured by Girardi et al. (1998, see text for details). Our measurement of the NGC 5044 is plotted as the large, filled triangle. Dotted, dashed and dot-dashed lines represent best fits to the cluster, group and combined samples respectively.

$\sim 4$ (e.g. Mulchaey and Zabludoff, 1998; Helsdon and Ponman, 2000a; Mahdavi and Geller, 2001; Ortiz-Gil et al., 2004; Hilton et al., 2005). At group masses, however, there is some disagreement as to whether or not the $L_X-\sigma_v$ relation is merely extension of the $\sigma_v^4$ relation found for clusters, or shallows to a slope of $\sim 2.4$ (e.g. Helsdon and Ponman, 2000b; Xue and Wu, 2000).

Osmond and Ponman suggest that, rather than an actual flattening in the $L_X-\sigma_v$ relation, the observed break at group masses could be a result of $\sigma_v$ poorly tracing the depth of the potential well. Conversely, Plionis and Tovmassian (2004) argue that the observed flattening in the $L_X-\sigma_v$ relation at low velocity dispersions is spurious, and is only observed as a result of a statistical bias in sampling of the low-$L_X$ limit.

Theoretically, one can predict not only the $L_X-\sigma_v$ correlation, but also the relationship between total mass of a system and its X-ray temperature or luminosity. Following self-similar arguments one can show that $M \propto T_X^{3/2}$ (Afshordi and Cen, 2002) and using $L_X \propto T_X^2$, arrive at $L_X \propto M^{3/2}$. As with the $L_X-\sigma_v$ relation, there
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Figure 3.10: X-ray luminosity variation with dynamical mass in the groups and clusters. Symbols are the same as Fig. 3.9. Lines are best fits to the $L_X-M$ data and dotted, dashed and dot-dashed lines represent fits to cluster, group and combined data respectively. Dynamical masses from Girardi et al. (1998) have been adjusted to $\delta = 178$ (see §3.3.5).

is disagreement as to the consistency of observational data with self-similar predictions. Horner et al. (1999) find a slope for their cluster sample consistent with the predicted power law slope of $\sim 1.5$ for the $M-T_X$ relation, while Nevalainen et al. (2000) and Finoguenov et al. (2001) find suggestions of a steeper relation, owing to the inclusion of groups in their X-ray samples. This slope change can be attributed to either an increase in the intrinsic scatter of the $M-T_X$ relation at group masses or a break in the relation where group and clusters follow fundamentally different trends.

While it is outside the scope of this thesis to examine the nature of the $L_X-\sigma_v$ and $L_X-M$ relations in detail, it is of interest to place the NGC 5044 group in this parameter space relative to other groups and clusters. Here we adopt the GEMS and ACC samples described in Section 3.3.5.

In Figs. 3.9 and 3.10 we show the X-ray luminosity–velocity dispersion and –dynamical mass relations for the combined GEMS and ACC sample, with best fits to the GEMS, ACC and combined samples overlayed. The NGC 5044 group is fit well by both the cluster and combined sample fits in the $L_X-\sigma_v$ relation. While our
fits suggest a difference in the group and cluster relations, the velocity dispersion measurements for low mass groups are highly uncertain (owing to their low number of member galaxies). The fits we find for the $L_X-M_{200}$ relation to the individual GEMS and ACC samples are consistent with the idea of a shallowing slope at group masses. As in the $L_X-\sigma_v$ relation, the NGC 5044 group is better fit by the ACC or combined sample trends.

Our results therefore suggest that, while the NGC 5044 group’s mass of $\sim 10^{14} M_\odot$ places it between the group and cluster regimes, the relationship of its X-ray and dynamical properties show it to be more akin to clusters than groups.

### 3.4 Galaxy properties

#### 3.4.1 Galaxy colours

With numerous studies of the photometric properties of early-type galaxies, it has been established that brighter, more massive galaxies are increasingly redder in colour (e.g. Visvanathan and Sandage, 1977; Baldry et al., 2004; Blanton et al., 2005). Further comparison of colour-magnitude relations (CMRs) between different clusters have shown nearly identical results (see e.g. Bower et al., 1992). In fact, Hogg et al. (2004) used a sample of SDSS galaxies to show that the slope of the CMR is roughly constant across a wide range of environments, a result that has been confirmed using larger samples from the SDSS (e.g. Gallazzi et al., 2006).

More detailed studies on the physical origin of the CMR have focused on comparing the stellar populations of galaxies at differing magnitudes (e.g. Bressan et al., 1996; Gallazzi et al., 2006) and have found that the CMR is primarily a mass–metallicity relation. Observed trends of increased metallicity towards high masses are consistent with feedback mechanisms, such as supernova driven winds that will be increasingly efficient at blowing gas out of low mass halos and suppressing star formation from enriched gas (e.g. Trager et al., 2000; Thomas et al., 2005). The increased blue-ward scatter about the CMR at low masses is dominated by age effects (Kodama and Arimoto, 1997; Gallazzi et al., 2006), where lower mass galaxies are still observed to be forming stars and higher mass galaxies are predominantly passively evolving (i.e. the “downsizing” effect). It is also worth noting that the CMR
**Figure 3.11:** $B - K$ vs. $M_K$ relation for galaxies in the NGC 5044 group. Elliptical, S0 and late-type galaxies are represented by filled circles, open circles and spirals respectively. $K$-band errors are taken from either the 2MASS and P05 catalogues, while $B$-band error estimates are adopted as the scatter between photometric measurements in FS90 and P00 (See Chapter 2.2.3) of 0.37 mags. The dashed line is the best fit CMR to the early-type data in the sample.

is characterised as a tight sequence of early-type galaxies, and thus the inclusion of poorly identified, faint late-type galaxies, e.g. late-type dwarf galaxies, could contribute to the observed scatter at faint magnitudes; in cases where careful removal of late-type galaxies and background objects is carried out, the scatter around both the bright and faint ends of the CMR is characterised solely by the photometric error at those magnitudes (e.g Janz and Lisker, 2009).

In Fig. 3.11 we show the $B - K$ vs. $M_K$ colour-magnitude relation derived for our NGC 5044 sample. Of the four galaxies with very red colours ($B - K > 4.6$), the two S0’s and spiral galaxy (open circles and spirals in Fig. 3.11 respectively) are seen edge on, so we expect increased reddening from dust in the disk. The fourth (elliptical) galaxy has a very large error associated with its $K$-band magnitude, and we suspect that the galaxy’s very red colour is due to this uncertainty. As discussed above, the CMR is defined for early-type galaxies, and thus our inclusion of both early- and late-types on Fig. 3.11 is, strictly speaking, incorrect. We have included late-type galaxies for comparison reasons only, and do not include them in our fits to the CMR that follow.
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A linear fit to the early-type galaxies gives a slope of $-0.13 \pm 0.03$ and intercept of $0.76 \pm 0.55$ (dashed line in Fig. 3.11), consistent with previous analyses of $B-K$ CMRs (e.g. Mobasher et al., 1986; Forbes et al., 2008). This also shows that dwarf galaxies in our sample are, on average, $\sim 0.4$ mags bluer that the most massive galaxies.

The correlation of galaxy colours with their local density, where redder galaxies are found predominantly in higher density environments, is now a well established trend (Dressler, 1980; Kauffmann et al., 2004; Smith et al., 2005; Blanton and Berlind, 2007). Recent studies using large 2dFGRS and SDSS samples have found increasing evidence that local density not only correlates with galaxy colour, but also galaxy star formation properties (e.g. Lewis et al., 2002; Gómez et al., 2003). For our sample, we calculate local density for each galaxy, $\Sigma_5$, using the projected distance of the 5th nearest neighbour galaxy. The relationship of $B-K$ colour with $\Sigma_5$ is shown in Fig. 3.12 We note that low density outskirts of the NGC 5044 group are the most poorly sampled, and so density measurements in these regions are likely an underestimate of the true density. Nevertheless, this figure certainly suggests agreement with the findings of Lewis et al. (2002) and Gómez et al. (2003), that above a certain local density (in this case $\Sigma_5 = 2 - 3$ galaxies Mpc$^{-2}$) galaxies transition from blue and star-forming, to passively evolving and red.

3.4.2 Spatial distribution of galaxies and segregation

With our large sample of confirmed 111 group members it is possible for us to explore the spatial and kinematic distribution of galaxies in significantly more detail than previous group studies. The most well known examples of spatial segregation, the morphology-density and morphology-radius relations (e.g. Dressler, 1980; Butcher and Oemler, 1984; Whitmore and Gilmore, 1991) have been well studied in galaxy clusters owing to the large numbers of galaxies typically available relative to the group environment. However studies focusing on galaxy groups also find significant evidence for segregation. In addition to spatial segregation, galaxies in clusters are found to be dynamically segregated with respect to both luminosity and morphology in simulations (Yepes et al., 1991; Fusco-Femiano and Menci, 1998), which is supported by observations of dynamical segregation in both groups and clusters (Girardi et al., 2003; Lares et al., 2004).
Here we examine evidence for both spatial and dynamical segregation amongst our galaxy group sample.

### Spatial segregation

To address the question of spatial segregation we subdivide our total sample by morphology (early- vs. late-types) and luminosity (where $M_B = -16.8$ mag is used as the break between dwarf and giant galaxies), the results of which are shown in Figs. 3.13 and 3.14.

When split by luminosity (Fig. 3.13), galaxies show no significant evidence for a radial bias, i.e. the two luminosity sub-samples are similarly distributed with radius. The hypothesis that dwarf and giant galaxies have the same radial distribution is only marginally rejected at the 70 percent level by a Kolmogorov-Smirnov (KS) test, confirming the visually apparent lack of a strong radial bias with luminosity. This is consistent with the known trend in dwarf-to-giant ratios (DGR) for groups and clusters, where the DGR is independent of position observed in the group (see e.g. FS91).

Splitting galaxies based on morphology (Fig. 3.14) gives a markedly different result in that galaxies are differently distributed at the $5\sigma$ level as determined using
3.4. Galaxy properties

Figure 3.13: Histogram showing number of galaxy type, either dwarf or giant, with projected radius. Second and third panels show recession velocity vs. projected radius for dwarf and giant sub-samples respectively. Dashed lines in panels two and three show the mean group velocity of 2577 km s\(^{-1}\).

A KS test. This is consistent with expectations from the morphology-density and morphology-radius relations ([Dressler, 1980]; [Butcher and Oemler, 1984]) and our findings from §3.4.1.

It is important to keep in mind that our group sample is assembled from a variety of sources with differing spatial coverage, selection and completeness (see Fig. 3.2 and Chapter 2), all of which could be inducing a radial bias in the results presented in Figs. 3.13 and 3.14. In particular, the region within \(\sim 600\) kpc of the group centre (approximately the area covered by FS90 and, therefore, our AAOmega observations) includes significant numbers of faint (dwarf) galaxies that are likely not included in the samples at larger radii. Repeating the KS test on only galaxies within the central 600\(\) kpc gives similar results to those above; dwarf and giant galaxies appear similarly distributed (at the \(\sim 60\) percent level) while early- and late-type galaxies show a difference in their radial distributions significant at the 3\(\sigma\) level with early-type galaxies more concentrated towards the centre.
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Figure 3.14: Same as Fig. 3.13 except galaxies are divided by morphology (early- vs. late-type) rather than luminosity.

Dynamical segregation

The dynamical segregation of galaxies in the NGC 5044 group has been examined previously by Cellone and Buzzoni (2005) using a sample of 26 early- and late-type galaxies. When dividing their sample based on morphology, they find early- and late-type galaxies exhibit velocity dispersions that differ at the 93 percent level (as measured using an $F$ test). Cellone and Buzzoni (2005) find no evidence for luminosity segregation in their early-type galaxies, however were unable to examine luminosity segregation between their early- and late-type samples due to low numbers of late-type galaxies.

Here we revisit the question of dynamical segregation in the NGC 5044 group using the morphology and luminosity sub-samples described above. We then compare the line-of-sight velocity distributions of sub-samples using two different methods to look for dynamically distinct behaviour. The first comparison is carried out using a KS test, which computes the likelihood of the two different samples being drawn from the same parent velocity distribution. The second test we use is an $F$-test, which gives the likelihood of the two distributions having significantly different variances. Table 3.5 summarises the results of the KS and $F$-test for our luminosity and morphology sub-samples.
Our results for morphological segregation computed using the F-test are consistent with Cellone and Buzzoni (2005), however increasing the sample of galaxies from 26 to 105 has decreased the significance slightly. There is marginal evidence of a variation in the distributions of early-type dwarf vs. giant galaxies and amongst early- vs. late-type dwarf galaxies, however these results are of low statistical significance ($\sim 1.6\sigma$).

When split by either luminosity or morphology our sample of NGC 5044 group galaxies is remarkably homogeneous, showing little strong evidence for any dynamical segregation. Results from the KS test show no evidence that any of the subsamples are statistically different distributions. In fact, the results for early- vs. late-type galaxies seem to suggest that the two distributions are actually similar at the $\sim 2\sigma$ level. Giant ($M_B < -17$) galaxies in our sample are similar with respect to their dynamics in the group irrespective of morphological type.
Table 3.5: Results from tests for dynamical segregation.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sub-sample</th>
<th>N₁</th>
<th>N₂</th>
<th>$\bar{c}_1$ (km s⁻¹)</th>
<th>$\sigma_1$ (km s⁻¹)</th>
<th>$\bar{c}_2$ (km s⁻¹)</th>
<th>$\sigma_2$ (km s⁻¹)</th>
<th>$L_{KS}$</th>
<th>$L_F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity Segregation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_B &lt; -16.8$ vs. $M_B &gt; -16.8$ all morphologies</td>
<td>37 58</td>
<td>2542±71</td>
<td>397±71</td>
<td>2540±40</td>
<td>302±36</td>
<td>46.1</td>
<td>84.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_B &lt; -16.8$ vs. $M_B &gt; -16.8$ late-type</td>
<td>18 17</td>
<td>2492±108</td>
<td>438±104</td>
<td>2580±77</td>
<td>317±64</td>
<td>27.6</td>
<td>8.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_B &lt; -16.8$ vs. $M_B &gt; -16.8$ early-type</td>
<td>19 41</td>
<td>2582±79</td>
<td>380±67</td>
<td>2522±53</td>
<td>296±38</td>
<td>67.8</td>
<td>91.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Morphological Segregation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>early- vs. late-types all luminosities</td>
<td>60 35</td>
<td>2542±48</td>
<td>317±38</td>
<td>2547±61</td>
<td>380±59</td>
<td>16.7</td>
<td>90.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>early- vs. late-types $M_B &gt; -16.8$</td>
<td>41 17</td>
<td>2522±53</td>
<td>296±38</td>
<td>2580±77</td>
<td>317±64</td>
<td>76.4</td>
<td>94.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>early- vs. late-types $M_B &lt; -16.8$</td>
<td>19 18</td>
<td>2582±79</td>
<td>368±67</td>
<td>2492±108</td>
<td>438±104</td>
<td>41.6</td>
<td>8.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes. Columns are as follows: (1) and (2) describe the samples being compared. (3) and (4) give the number of galaxies in each sub-sample. (5) – (8) give the mean velocities and dispersions of the two different sub-samples. (9) is the significance, from a KS Test, that the two distributions are drawn from different distributions. (10) gives the significance, via an F-test, that the distributions have different variances.
3.5 Discussion and conclusions

In this Chapter we have reassessed membership of the NGC 5044 group using an updated list of potential members comprised of new spectroscopic observations, existing spectra from the 6dFGS and available literature recession velocities. With this substantial dataset we are able to define the NGC 5044 group as containing 111 members with $M_B \leq -13.5$ mag, nearly a three-fold increase over previous numbers of confirmed group members. In spite of this significant increase in group membership, we find no significant change in dynamical parameters including mass, virial radius and crossing time relative to work presented by Brough et al. (2006a).

An analysis of common dynamical indicators such as crossing time, line-of-sight velocity distribution, position of the X-ray peak relative to the centroid suggest that the NGC 5044 group is relaxed and virialized despite the observed $150 \text{ km s}^{-1}$ peculiar velocity of the brightest group galaxy NGC 5044. This conclusion of virialization is consistent with XMM X-ray contours for the group, which are very regular and undisturbed. We note, however, that none of our tests for virialization are sensitive to effects along the line-of-sight, and so the true dynamical state of the group remains somewhat unknown. Taking the above indicators at face value, however, the group’s virialization suggests that the NGC 5044 group has experienced no major sub-group mergers in several crossing times ($\sim 1 \text{ Gyr}$).

While the dynamical indicators discussed above will give hints as to the timescale of major merger activity, it is likely that low-mass sub-group mergers will not significantly disrupt the virialization of the system as determined via these indicators. By computing the Dressler-Shectman $\Delta$ statistic, we have been able to visually and statistically search for space-velocity substructure in the group. In doing so, we find evidence for a low mass substructure $\sim 1.4 \text{ Mpc}$ from NGC 5044 group centre. It is possible that a quantitative link between this observed substructure and NGC 5044’s peculiar velocity exists, supported by recent observations that the distribution of X-ray gas in the NGC 5044 group displays a “sloshing” type cold front indicative of relatively recent dynamical activity (Gastaldello et al., 2009). However, with the data presented here we are unable to place strong constraints on such a scenario.

Two body interactions are expected to lead to dynamical and luminosity segregation in mature groups such as NGC 5044 (e.g. Fusco-Femiano and Menci, 1998;...
In examining the NGC 5044 group’s galaxy population however, we find that galaxies are primarily segregated with respect to their morphologies, and there is no strong evidence for segregation in either dynamics or luminosity.

While luminosity segregation is an expected outcome of mergers in groups (e.g. Fusco-Femiano and Menci, 1998; Lares et al., 2004), and therefore its absence is somewhat curious in NGC 5044, Ludlow et al. (2009) have used N-body simulations to show that it is possible to eject sub-halos from a group, via multi-body interactions, resulting in significant numbers of associated sub-halos residing in the outskirts of the group (as far as 5 times the virial radius). In relaxed groups such as NGC 5044, galaxies have had significant time for two-body interactions to take place, and so the ejection of galaxies from the group centre is likely to dilute any observable trends in the galaxy distribution. In addition, this complicates the common interpretation of group-centric radius as a tracer of accretion history as it is no longer clear that galaxies in the outskirts are actually the most recent galaxies to have been accreted into the group potential.

As a galaxy population, early-type galaxies in the NGC 5044 group are well described by a linear $B - K$ colour-magnitude relation, and are consistent with previous interpretations for the slope in the CMR due to decreasing metallicity or age at lower galaxy masses. Correlations of $B - K$ colour with local density seem to further suggest that the majority of these bluer, fainter galaxies are residing in the outskirts of the group, where densities are less than 2 – 3 galaxies Mpc$^{-2}$. This is consistent with findings for groups and cluster outskirts in the 2dFGRS and SDSS surveys (e.g. Lewis et al. 2002; Gómez et al. 2003), however our low sample size prohibits a more quantitative analysis of this effect.

In general, the data presented in this Chapter paint a picture of the NGC 5044 as undergoing a relatively quiescent evolution in recent times, supported in particular by the lack of discernible dynamical substructure in its galaxy distribution unlike the Coma or Virgo clusters. Having established this “baseline” of group properties, we now turn our focus to a more quantitative analysis of NGC 5044’s galaxy population using absorption- and emission-line features to derive stellar population parameters.

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Ludlow et al. (2009) define associated halos as those that have, at some point, passed within the virial radius of the central halo.
Lick indices and the stellar populations of Galactic GCs

Chemical analyses of unresolved extragalactic targets have long been dependent on the accurate modelling of stellar populations. Initial empirical approaches to the modelling of integrated light (Spinrad and Taylor, 1971) primarily made use of broadband colours as a proxy for a stellar population’s age and metallicity. However, the highly degenerate properties of broadband colours – old, metal-poor and young, metal-rich populations are photometrically identical at optical wavelengths – severely limit the accuracy of age and metallicity measurements from photometric studies alone. More recent stellar population models have attempted to address this shortcoming by modelling continuous spectral energy distributions (SEDs) at medium to high resolution (5 – 1 Å), allowing a much finer accounting of age and metallicity effects on integrated light.

The development of spectral indices, in particular Lick index absorption features (Burstein et al., 1984; Trager et al., 1998), and their incorporation into stellar population models has afforded the much needed leverage to effectively break the age–metallicity degeneracy. Single stellar population models (SSPs) including Lick indices were first assembled by Worthey (1994), who modelled 21 absorption indices and sought to identify those features that were particularly age (e.g. Balmer lines) or metallicity (e.g. Fe4668, Fe5015, Fe5709 etc.) sensitive and therefore the most useful for overcoming the observed degeneracy. More recent works (e.g. Maraston, 1998; Vazdekis, 1999; Bruzual and Charlot, 2003; Thomas et al., 2003, 2004; Maraston, 2005) have further refined these models, allowing for a more detailed study of the effects of age and metallicity on the observed integrated light.
Chapter 4. Lick indices and the stellar populations of Galactic GCs

Lee and Worthey (2005) have focused on including additional age-sensitive indices (the higher-order Balmer lines \( \text{H}\delta \) and \( \text{H}\gamma \)) and increasingly complex evolutionary processes such as mass loss and horizontal-branch morphology.

\( \alpha \)-elements (N, O, Mg, Ca, Na, Ne, S, Si and Ti for the purposes of SSP models), or more accurately the ratio of \( \alpha \)-elements to iron peak elements (Cr, Mn, Fe, Co, Ni, Cu and Zn), serve as useful tracers of star-formation efficiency due to their strong dependence on SNII; stellar systems with high \( \alpha \)-to-iron ratios ([\( \alpha/\text{Fe} \)]) form their stars over relatively short timescales (Thomas et al., 2005), while systems with lower [\( \alpha/\text{Fe} \)] undergo more extended star-formation episodes. Efforts have therefore been taken to account for known variations in \( \alpha \)-element abundance with respect to Fe-peak elements and their particular effect on Lick index measurements. Tripicco and Bell (1995) computed the effects of variation in C, N, O, Mg, Fe, Ca, Na, Si, Cr and Ti on the 21 indices modelled by Worthey (1994). These relative index sensitivities were then used by Trager et al. (2000) to modify the SSPs of Worthey (1994), facilitating the measurement of ages, metallicities and \( \alpha \)-element abundances for a sample of \( \sim 40 \) elliptical galaxies through a comparison of \( \text{H}\beta \), \( \text{Mg}\, b \) and iron indices. Subsequent calculations of abundance effects have mimicked the work of Tripicco and Bell (1995), adding sensitivity calculations for higher-order Balmer lines (e.g. Houdashelt et al., 2002; Korn et al., 2005) and expanding index sensitivities to encompass a broad range of population metallicities (Korn et al., 2005). These “\( \alpha \)-enhanced” models have since been used to trace the elemental abundance patterns as a proxy for the evolutionary histories of both galaxies and globular clusters (e.g. Thomas et al., 2005; Spolaor et al., 2008; Proctor et al., 2008).

In order to establish the reliability of parameters derived through comparison to Single Stellar Population models (SSPs), it is first important to verify both the method used to interpret spectral features in terms of age, metallicity and \( \alpha \)-element abundance, as well as test the degree to which different SSP models are able to describe integrated stellar populations. Thankfully, both of these tasks can be accomplished using integrated observations of Galactic globular clusters (GCs). Although recent observational evidence shows that the most massive GCs may host multiple stellar population sequences (Villanova et al., 2007; Milone et al., 2008), observations of integrated GC light are largely dominated by a single, coeval and chemically homogeneous stellar population readily comparable to the single bursts
of star formation modelled by SSPs. Furthermore, the proximity of GCs in our own Galaxy allows accurate measurement of their ages, metallicities and $\alpha$-element abundances through independent analyses of colour-magnitude diagrams (CMDs) and high-resolution resolved spectroscopy.

The comparative analysis of SSP derived GC properties and their CMD or spectroscopically resolved counterparts has already been carried out by Proctor et al. (2004a), who fit a sample of 24 Galactic GC spectra. Proctor et al. used drift-scanned GC spectra from Cohen et al. (1998, hereafter CBR98) and Puzia et al. (2002), which were fit to the SSP models of Vazdekis (1999), Bruzual and Charlot (2003) and Thomas et al. (2003) using a novel multi-index $\chi^2$ fitting technique as opposed to classical 2-index fits e.g. Trager et al. (2000); Thomas et al. (2003). They found that it was possible to recover ages, metallicities and $\alpha$-element abundances to within $\sim 0.1$ dex of properties derived using resolved observations (both spectroscopic and photometric). However, the relatively small sample size utilised by Proctor et al. and the relative lack of independent age and $\alpha$-element abundance measurements prohibited a reliable, statistical comparison to literature trends.

The aims of this Chapter are two-fold: Firstly, we introduce details of the Lick absorption features used for measurement of age, metallicity and $\alpha$-element abundance. Secondly, we expand on the work of Proctor et al. (2004a) by comparing recent, high signal-to-noise spectra ($S/N \sim 100$) of 42 Galactic GCs taken by Puzia et al. (2002) and Schiavon et al. (2005) to an updated suite of SSP models from Thomas et al. (2004), Lee and Worthey (2005) and Vazdekis et al. (in preparation). In order to facilitate an even comparison between SSP models, $\alpha$-element enhancement calculations of both Houdashelt et al. (2002) and Korn et al. (2005) are applied to the three model sets listed above. These uniformly $\alpha$-enhanced models then allow a comparison of integrated GC ages, metallicities and $\alpha$-element abundances with similar parameters derived from CMD analyses and resolved stellar spectra (De Angeli et al., 2005) and resolved stellar spectra (Pritzl et al., 2003). By comparing the predictions of a variety of models to these “standard” measurements we are able to gauge both the reliability of parameters derived solely from integrated spectral features as well as gain an understanding of the particular biases of the SSP models used.
4.1 Absorption-line measurement and the Lick/IDS system

In this thesis we use Lick absorption-line indices to characterise the properties of stellar systems based on their integrated light. The classical Lick indices (Worthey, 1994; Trager et al., 1998), as well as higher order Balmer lines (Worthey and Ottaviani, 1997), are defined based on their sensitivity to either age or metallicity so as to provide the ideal set of features that allow degeneracy-independent measurements of age and metallicity.

In Table 4.1 we show the side and central band definitions for the 21 classical Lick indices defined by Worthey (1994) and Trager et al. (1998) along with the 4 higher order Balmer lines defined by Worthey and Ottaviani (1997).

Worthey (1994) used 460 stars observed using the Image Dissector Scanner (IDS) at the Lick Observatory and index definitions to construct empirical fitting functions describing the variation of Lick indices as a function of log $g$, $T_{\text{eff}}$ and metallicity. These fitting functions form the basis of many SSP models, and in using these SSPs to interpret absorption features it is important that newly observed spectra are calibrated to match the spectral characteristics of the IDS. This calibration is undertaken by comparing the indices of re-observed Lick standard stars — i.e. stars from the Worthey (1994) stellar library — with originally measured and published indices.

4.1.1 Velocity dispersion corrections

In order to properly compare measured indices with SSP models it is important that the total broadening of any given absorption feature matches the wavelength dependent broadening of the Lick/IDS system. Galaxies with combined instrumental and velocity dispersion broadening, $(\sigma^2_I + \sigma^2_v)^{1/2}$, less than the target Lick resolution, $\sigma_L$, are broadened as necessary using a wavelength dependent Gaussian kernel of width $\sigma_B$ to match the description of the Lick/IDS resolution given by Worthey and Ottaviani (1997) such that

$$\sigma^2_B = \sigma^2_L - \sigma^2_I - \sigma^2_v.$$  \hspace{1cm} (4.1)
4.1. Absorption-line measurement and the Lick/IDS system

Table 4.1: Blue, central and red passband definitions for 21 classical Lick indices and 4 higher order Balmer lines. Labels denote indices measured in either equivalent width (Å) or magnitudes.

<table>
<thead>
<tr>
<th>Index</th>
<th>Blue Continuum</th>
<th>Central Passband</th>
<th>Red Continuum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hα (Å)</td>
<td>4041.600 – 4079.750</td>
<td>4083.500 – 4122.250</td>
<td>4128.500 – 4161.000</td>
</tr>
<tr>
<td>Hβ (Å)</td>
<td>4057.250 – 4088.500</td>
<td>4091.000 – 4112.250</td>
<td>4114.750 – 4137.250</td>
</tr>
<tr>
<td>CN1 (mag)</td>
<td>4080.125 – 4117.625</td>
<td>4142.125 – 4177.125</td>
<td>4244.125 – 4284.125</td>
</tr>
<tr>
<td>CN2 (mag)</td>
<td>4083.875 – 4096.375</td>
<td>4142.125 – 4177.125</td>
<td>4244.125 – 4284.125</td>
</tr>
<tr>
<td>Ca4227</td>
<td>4211.000 – 4219.750</td>
<td>4222.250 – 4234.750</td>
<td>4241.000 – 4251.000</td>
</tr>
<tr>
<td>G4300</td>
<td>4266.375 – 4282.625</td>
<td>4281.375 – 4316.375</td>
<td>4318.875 – 4335.125</td>
</tr>
<tr>
<td>Hα (Å)</td>
<td>4283.500 – 4319.750</td>
<td>4319.750 – 4363.500</td>
<td>4367.250 – 4419.750</td>
</tr>
<tr>
<td>Ca4455</td>
<td>4445.875 – 4454.625</td>
<td>4452.125 – 4474.625</td>
<td>4477.125 – 4492.125</td>
</tr>
<tr>
<td>Fe4531</td>
<td>4504.250 – 4514.250</td>
<td>4514.250 – 4559.250</td>
<td>4560.500 – 4579.250</td>
</tr>
<tr>
<td>C4668</td>
<td>4611.500 – 4630.250</td>
<td>4634.000 – 4720.250</td>
<td>4742.750 – 4756.500</td>
</tr>
<tr>
<td>Hβ (Å)</td>
<td>4827.875 – 4847.875</td>
<td>4847.875 – 4876.625</td>
<td>4876.625 – 4891.625</td>
</tr>
<tr>
<td>Fe5015</td>
<td>4946.500 – 4977.750</td>
<td>4977.750 – 5054.000</td>
<td>5054.000 – 5065.250</td>
</tr>
<tr>
<td>Mg1 (mag)</td>
<td>4895.125 – 4957.625</td>
<td>5069.125 – 5134.125</td>
<td>5301.125 – 5366.125</td>
</tr>
<tr>
<td>Mg2 (mag)</td>
<td>4895.125 – 4957.625</td>
<td>5154.125 – 5196.625</td>
<td>5301.125 – 5366.125</td>
</tr>
<tr>
<td>Mg b (Å)</td>
<td>5142.625 – 5161.375</td>
<td>5160.125 – 5192.625</td>
<td>5191.375 – 5206.375</td>
</tr>
<tr>
<td>Fe5270</td>
<td>5233.150 – 5248.150</td>
<td>5245.650 – 5285.650</td>
<td>5285.650 – 5318.150</td>
</tr>
<tr>
<td>Fe5335</td>
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<td>5312.125 – 5352.125</td>
<td>5353.375 – 5363.375</td>
</tr>
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<td>Fe5406</td>
<td>5376.250 – 5387.500</td>
<td>5387.500 – 5415.000</td>
<td>5415.000 – 5452.000</td>
</tr>
<tr>
<td>Fe5709</td>
<td>5672.875 – 5696.625</td>
<td>5696.625 – 5720.375</td>
<td>5722.875 – 5736.625</td>
</tr>
<tr>
<td>Fe5782</td>
<td>5765.375 – 5775.375</td>
<td>5776.625 – 5796.625</td>
<td>5797.875 – 5811.625</td>
</tr>
<tr>
<td>Na D (Å)</td>
<td>5860.625 – 5875.625</td>
<td>5876.875 – 5909.375</td>
<td>5922.125 – 5948.125</td>
</tr>
<tr>
<td>TiO1 (mag)</td>
<td>5816.625 – 5849.125</td>
<td>5936.625 – 5994.125</td>
<td>6038.625 – 6103.625</td>
</tr>
<tr>
<td>TiO2 (mag)</td>
<td>6066.625 – 6141.625</td>
<td>6189.625 – 6272.125</td>
<td>6372.625 – 6415.125</td>
</tr>
</tbody>
</table>

Spectra for which $\sigma_L \simeq \sigma_i^2 + \sigma_v^2)^{1/2}$ require no additional corrections to their index measurements. If the total broadening of the galaxy spectra exceeds the Lick resolution, then spectra are left un-broadened and a correction factor, $C_i$ is computed using a third order polynomial such that

$$C_i = x_0 + x_1 \sigma_C + x_2 \sigma_C^2 + x_3 \sigma_C^3,$$  (4.2)

where $\sigma_C = (\sigma_i^2 + \sigma_v^2 - \sigma_L^2)^{1/2}$. This correction is then applied to measured indices either additively, $C_i = I_L - I_{Meas}$, or multiplicatively, $C_i = I_L/I_{Meas}$ depending on the index where $I_L$ and $I_{Meas}$ represent the corrected Lick index value and the measured value respectively. Molecular band indices (CN, Mg1, Mg2) and higher order Balmer lines (Hδ, Hγ) had additive corrections applied, while for all other indices multiplicative corrections were used.

As a test of this method, Proctor and Sansom (2002) compare stellar and galaxy spectra broadened using this technique, finding good agreement between the two. For further details see Proctor and Sansom (2002) and Proctor (PhD thesis).
4.2 Stellar population models

In order to interpret measured Lick indices in terms of the ages, metallicities and α-element abundances they describe, we compare observed index measurements to those published in SSP models. Here, models from Thomas et al. (2004, hereafter TMK04), Lee and Worthey (2005, hereafter LW05) and Vazdekis et al. (in preparation; hereafter V07) have been chosen for application to the Galactic GC data used later in this Chapter. TMK04 and LW05 models are both computed using the Worthey (1994) fitting functions and provide Lick/IDS system index values for a range of ages and metallicities. Vazdekis et al. provide their models as SEDs, from which we then measure Lick indices. We have decided not to include the commonly used models of Vazdekis (1999) or Bruzual and Charlot (2003) as they have been studied in a similar fashion by Proctor et al. (2004a).

Below is a summary of the essential parameters for each of the three SSP models mentioned above.

**TMK04:** These are based on previous work by Thomas et al. (2003, hereafter TMB03). Models cover the metallicity range $-2.25 \leq [Z/H] \leq 0.65$ with ages from 1 to 15 Gyr and are based on isochrones from Cassisi et al. (1997), Bono et al. (1997) and Salasnich et al. (2000). TMK04 include horizontal branch effects, providing empirically calibrated Balmer lines modelled for both red and blue horizontal branch morphologies using the stellar mass loss parameter $\eta$ (Reimers, 1975). Variations in abundance ratios are tabulated using updated response functions that include the higher-order Balmer lines and a metallicity dependence as calculated by Korn et al. (2005). These models cover all 25 Lick indices in a wavelength range of $\lambda\lambda$ 4000 – 6500 Å.

**LW05:** The Lee & Worthey models cover a metallicity range of $-2.5 \leq [Fe/H] \leq 0.3$ and an age range of 1 to 12 Gyr. Recent $Y^2$ isochrones (Yi et al., 2001, Kim et al., 2002) are adopted along with post red giant evolutionary tracks from Yi et al. (1997). An additional scaling factor $\eta$ is used to account for stellar mass loss and aids in matching observed horizontal-branch morphology in Galactic GCs. SSPs include alpha enhancements of $[\alpha/Fe] = 0.0, 0.3$ and 0.6 applied at super-solar metallicities.
ties using updated response functions from Houdashelt et al. (2002). At sub-solar metallicities, \( \alpha \)-element abundances are super-solar and reflect the local abundance-ratio pattern, which includes some metallicity dependence. The SSPs model 25 Lick indices from \( \text{H} \delta_{A} \) to \( \text{TiO}_2 \).

**V07:** Models from Vazdekis et al. are based on the previous models of Vazdekis (1999) and Vazdekis et al. (2003). These models are presented as SEDs and cover a metallicity range of \(-2.3 \leq [Z/H] \leq 0.2\) and ages from 0.1 to 17.5 Gyrs using Padova group isochrones from Girardi et al. (2000). These models are derived using the recent MILES spectral library (Sánchez-Blázquez et al., 2006). Non-solar abundance ratios are not accounted for in these models, so SSPs represent the local abundance pattern.

### 4.2.1 SSP model calibrations

For the SSP models outlined above, calibrations have been carried out in order to verify the accuracy of their index predictions. This is a key step in the construction of these SSP models, as the results obtained from their use on extragalactic sources are generally blind (i.e. there are no corroborating methods like CMDs or resolved spectroscopy available). For their calibrations, both TMK04 and LW05 make use of the P02 Galactic GC data as measured using the Worthey (1994) index definitions. The P02 observations were taken with specific care given to their luminosity sampling in order to obtain accurate cluster spectra with account of stochastic effects. This careful sampling means that spectra are representative of the total cluster population and therefore ideal for the calibration of Lick index models.

Calibrations of the TMK04 models have been well documented in Maraston et al. (2003), TMB03 and TMK04, which involve assuming an old GC age (12 Gyrs) and comparing measured GC indices to SSP predictions. In Maraston et al. (2003), these comparisons are carried out using index-index comparison with \(<\text{Fe}>\) (iron-sensitive indices) or \(\text{Mg} b\) (all other indices) and metallicity comparison with CMD \([\text{Fe}/\text{H}]\) determinations (their Figs. 1, 7 – 11). Additional evaluations of the higher-order Balmer lines are carried out through \(\text{H}\delta, \text{H}\gamma\) vs. \([\text{MgFe}]\) index comparisons (their Fig. 13). In all of these Maraston et al. (2003) note that the GC data of P02 lie as expected in relation to their SSPs, predicting metallicities and \(\alpha\)-element
abundances consistent with those from CMD and resolved spectral studies. These results are reiterated in TMB03, and the Balmer lines are re-calibrated in TMK04, with the same good agreement being found.

Lee and Worthey (2005) perform similar calibrations for their SSP models, comparing Lick index measurements of the CBR98 and P02 datasets to their SSP models. This is done through a comparison of Lick indices to [Fe/H] as predicted by their SSPs, using metallicities from Harris (1996) for the GC data. They, like KMT04, find good agreement between their SSPs and GCs and note that their models require no zero-point offset to match the GC data.

Unfortunately, information regarding the calibration of V07 models is unavailable at the time of writing.

4.2.2 Non-solar abundance ratios

An important consideration in fitting our sample of Galactic GCs is the handling of non-solar abundance ratios. It is well known that GCs exhibit elemental abundances that differ from those measured in the Sun (Pilachowski et al., 1983; Gratton, 1987), and tabulated response functions have allowed for these variations to be included in the SSP models. Tripicco and Bell (1995, hereafter TB95) modelled response functions for the Lick/IDS index system, providing fractional index variations for the 21 classical Lick indices with respect to 10 elements (C, N, O, Mg, Ca, Na, Si, Ti, Cr and Fe) for three different stellar types (cool dwarf, main-sequence turnoff dwarf and cool giant). The TB95 fractional responses were calculated by doubling each element, $X_i$, in turn ([X$_i$/Fe] = +0.3) and measuring the resultant effects on each index. TB95 carried out their calculations using 5 Gyr old isochrones, adjusting the relative contributions of dwarf, main-sequence turnoff and giant stars in order to reproduce a range of ages, metallicities and $\alpha$-element ratios.

The original calculations of TB95 have since been updated by Houdashelt et al. (2002, hereafter H02) using more recent atomic line lists. H02 have also varied the method by which carbon enhancement is calculated; rather than double carbon (+0.3 dex) they have chosen to enhance carbon by only +0.15 dex, seeking to avoid modelling discrepancies that arise as C/O approaches 1. The final response functions presented by H02 also include several indices omitted by TB95 in their original calculations, namely the higher-order Balmer lines ($H_\delta_{A,F}$ and $H_\gamma_{A,F}$) and TiO.
The simplifications made by TB95 and H02, primarily modelling index variations using 5 Gyr isochrones and fixed metallicity, may introduce systematic errors when applied to model grids spanning a large range in age and metallicity. Korn et al. (2005, hereafter KMT05) have formulated response functions independently of the TB95 calculations and, in doing so, test some of the modelling assumptions of TB95. KMT05 confirm the validity of using a single isochrone, finding at most $\sim 1$ percent deviations in index sensitivity between calculations carried out on both 1 Gyr and 5 Gyr isochrones. In addition, they include calculations for high-order Balmer lines ($H_\delta_A, F, H_\gamma_A, F$), TiO and have added metallicity dependence to their fractional responses, recalculating the same tables as TB95 and H02 for six different metallicities from $-2.25 \leq [Z/H] \leq 0.67$.

In this Chapter we apply both the KMT05 and H02 fractional sensitivities to a variety of models using the methods outlined in Trager et al. (2000, hereafter T00) and TMB03. In summary, these methods involve the adjustment of $\alpha$-element abundances at a fixed metallicity using the relation

$$[Z/H] = [Fe/H] + A[\alpha/Fe]$$

which, applied at constant metallicity leads to (T00):

$$A = -\frac{\Delta[Fe/H]}{\Delta[\alpha/Fe]}$$

where A varies depending on which elements are selected as enhanced or depressed. In this work we consider N, O, Mg, Ca, Na, Si and Ti as $\alpha$-group elements, while Cr and Fe are depressed. We leave C unchanged (i.e. solar-scaled). This enhancement scheme mimics the work of TMK04, allowing us to compare our enhanced models to published TMK04 models that use these same index sensitivity calculations. Using Eqn. 4.4 we find $A=0.934$ when C is excluded from the enhanced group and solar-scaled. Following TMB03, the enhanced index $I_{\text{new}}$ is calculated from the measured index $I_{\text{ssp}}$ using

$$I_{\text{new}} = I_{\text{ssp}} \prod_{i=1}^{n} \exp[R_{0.3}(i)]^{(\Delta[X_i]/0.3)},$$
where the quantity \( R_{0.3}(i) \) refers to the index change resultant from increasing the abundance of the \( i^{th} \) element by 0.3 dex (adopting notation from T00). This equation is arrived at by assuming \( \ln I \) is a linear function of \([X_i]\) and using a Taylor expansion to approximate the effects of abundance ratio changes (see TMB03 for details).

One of the problems that arises when applying abundance ratio adjustments is that, in some cases, Lick indices have negative values. In applying the expansion of \( \ln I \) (Eqn. 4.5) however, it is implicit that the index values cannot be negative, and in fact asymptotically approach zero at low abundances (TMB03; T00). KMT05 handle this problem by applying their computed index response directly to the flux of their absorption lines, yielding a positive result. Lacking the means to apply corrections in this manner, we have adopted the method used by TMB03, in which the lowest value of a particular index at a given age is taken as the zero point, and all other indices are scaled to reflect this zero point shift. In the case of the high-order Balmer lines this occurs at the highest metallicity, while for most other Lick indices it occurs at the lowest. For C4668 and NaD, the low points do not occur at either end of the metallicity scale, indicating an inflection point in the indices at an intermediate metallicity. For these indices, values from the local minima are adopted. The zero-point index adjustment is defined as \( \delta \equiv I_{low} - |I_{low}| \), and is applied following equation 9 from TMB03:

\[
I_{\text{new}} - \delta = (I_{\text{ssp}} - \delta) \prod_{i=1}^{n} \exp \left( \frac{1}{I_0 - \delta} \frac{\partial I}{\partial [X_i]} 0.3 \right)^{(\Delta[X_i]/0.3)},
\]

where \( I_0 \) is the absolute index value taken from the index response tables. The key difference between TMB03’s and our application of this zero-point adjustment is that TMB03 adjust each evolutionary phase individually, while here we are left to apply this adjustment to the integrated index measurements.

In estimating fractional index sensitivities, we include several additional effects not discussed above. Firstly, the fractional responses of KMT05 have been adopted strictly in a differential sense, using the SSP index values \( (I_{\text{ssp}}) \) in place of their \( I_0 \) values. While shifting from \( I_0 \) to \( I_{\text{ssp}} \) should generally improve accuracy, for indices in which the lowest index value is very small (i.e. \( I_{\text{ssp}} - \delta \leq 0.05 \)) the calculated

\[ R_{0.3}(i) = \frac{1}{I_0} \frac{\partial I}{\partial [X_i]} 0.3 \]
4.2. Stellar population models

Figure 4.1: The adopted contributions of each stellar type with age as approximated using Fig. 41 of Worthey (1994). This allows for the luminosity of older populations to be increasingly affected by stars occupying the giant-branch phase of stellar evolution, and proved important in matching the behaviour of the TMK04 models.

Fractional responses are overestimated, since \( R_{0.3}(i) \propto (I_{\text{ssp}} - \delta)^{-1} \). To account for this we apply a correction to our zero-point index offsets such that

\[
\delta \equiv I_{\text{low}} - |I_{\text{low}}| - 1. \quad (4.7)
\]

This adjustment increases all indices relative to the zero point, and should have little effect on the applied fractional enhancements except in the cases of very low index values.

Secondly, additional considerations were included to account for variations in the flux contribution of a given evolutionary type with respect to both age and wavelength. This was done using estimated values from Fig. 41 from Worthey (1994). The results of our approximations are shown in Figs. 4.1 and 4.2. The effect of this added age and wavelength dependence is generally 5 – 10 percent, however can be as much as 50 percent for the bluest indices in the youngest populations. We stress that these are approximations only, made to include some handling of varying flux contributions for different populations.

Since the published TMK04 models make use of the KMT05 enhancement calculations, our goal in applying enhancements is to mimic the TMK04 models with our own TMK+KMT05 calculations. To this end, we have compare the TMK+KMT05 models to the TMK04 models for twice solar ([E/Fe] = 0.3) grids. The results of these comparisons are shown in Columns 2 and 3 ([Z/H] \leq 0 and [Z/H] > 0 re-
Figure 4.2: The adopted contribution of each stellar type as it varies with wavelength. These show the same trends as noted by Worthey (1994), that for younger populations the equivalence point for giant and main sequence stars shifts to higher wavelengths.

spectively) of Table 4.2. We find the agreement to be acceptable, particularly at lower metallicities where the majority of our GCs lie. In nearly all cases deviations between the TMK04 and TMK+KMT05 models are less than the adopted errors for conversion to the Lick/IDS system, and should therefore have negligible effects on parameters derived from fits (i.e. age, metallicity and $\alpha$-enhancement). The C4668 index is an exception to this, showing significant deviations in the higher metallicity regime. This is indicative of the high sensitivity of the C4668 index to small variations in $\alpha$-element abundance.

For the remainder of this Chapter SSPs that are used as originally published will be referred to by their respective references (i.e. TMK04, LW05 and V07), while models that we have altered through the use of the H02 and KMT05 index response functions will be referred to by a combination of the model and enhancement calculation reference (e.g. TMK+H02, LW+KMT05, V+H02, etc.).
4.2. Stellar population models

Table 4.2: Comparison between TMK04 and TMK+KMT05 models. Columns 2 and 3 give the $\sigma_{\text{rms}}$ between [E/Fe] = 0.3 TMK04 and TMK+KMT05 models in two different metallicity ranges. In most cases the errors in our enhancement application are well within our Lick calibration errors and, therefore, have little effect on the derived parameters.

<table>
<thead>
<tr>
<th>Lick Index</th>
<th>$\Delta_{\text{TMK+KMT05}}$ [Z/H] $\leq 0$</th>
<th>$\Delta_{\text{TMK+KMT05}}$ [Z/H] $&gt; 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H68 (Å)</td>
<td>0.068</td>
<td>0.221</td>
</tr>
<tr>
<td>H65b (Å)</td>
<td>0.024</td>
<td>0.074</td>
</tr>
<tr>
<td>CN1 (mag)</td>
<td>0.001</td>
<td>0.005</td>
</tr>
<tr>
<td>CN2 (mag)</td>
<td>0.001</td>
<td>0.005</td>
</tr>
<tr>
<td>Ca4227 (Å)</td>
<td>0.019</td>
<td>0.043</td>
</tr>
<tr>
<td>G4300 (Å)</td>
<td>0.059</td>
<td>0.081</td>
</tr>
<tr>
<td>H7A (Å)</td>
<td>0.027</td>
<td>0.140</td>
</tr>
<tr>
<td>H7F (Å)</td>
<td>0.014</td>
<td>0.023</td>
</tr>
<tr>
<td>Fe4383 (Å)</td>
<td>0.048</td>
<td>0.162</td>
</tr>
<tr>
<td>Ca4455 (Å)</td>
<td>0.002</td>
<td>0.004</td>
</tr>
<tr>
<td>Fe4531 (Å)</td>
<td>0.012</td>
<td>0.005</td>
</tr>
<tr>
<td>Ca4668 (Å)</td>
<td>0.133</td>
<td>0.444</td>
</tr>
<tr>
<td>H9 (Å)</td>
<td>0.010</td>
<td>0.006</td>
</tr>
<tr>
<td>Fe5015 (Å)</td>
<td>0.027</td>
<td>0.043</td>
</tr>
<tr>
<td>Mg1 (mag)</td>
<td>0.003</td>
<td>0.007</td>
</tr>
<tr>
<td>Mg2 (mag)</td>
<td>0.002</td>
<td>0.005</td>
</tr>
<tr>
<td>Mg b (Å)</td>
<td>0.045</td>
<td>0.151</td>
</tr>
<tr>
<td>Fe5270 (Å)</td>
<td>0.018</td>
<td>0.011</td>
</tr>
<tr>
<td>Fe5335 (Å)</td>
<td>0.019</td>
<td>0.032</td>
</tr>
<tr>
<td>Fe5406 (Å)</td>
<td>0.016</td>
<td>0.011</td>
</tr>
<tr>
<td>Fe5709 (Å)</td>
<td>0.012</td>
<td>0.002</td>
</tr>
<tr>
<td>Fe5782 (Å)</td>
<td>0.012</td>
<td>0.005</td>
</tr>
<tr>
<td>Na D (Å)</td>
<td>0.007</td>
<td>0.014</td>
</tr>
<tr>
<td>TiO1 (mag)</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>TiO2 (mag)</td>
<td>0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Chapter 4. Lick indices and the stellar populations of Galactic GCs

4.3 Galactic GC spectral data

The focus for the remainder of this Chapter is on the comparison of SSP derived Galactic GC properties with independent determinations, either from resolved spectroscopy or deep imaging. The integrated GC spectra used here are taken from two different sources. 

Schiavon et al. (2005, hereafter S05) provide spectra for 41 GCs chosen to represent a range of parameters (e.g. age, metallicity, Galactocentric distance, etc.). These spectra were obtained at the Cerro Tololo Inter-American Observatory (CTIO) Blanco 4-m telescope with the Ritchey-Chretien spectrograph and cover a wavelength range of $\lambda\lambda 3350 – 6430$ Å at a resolution of $\sim 3.1$ Å per pixel for central wavelengths. This allows measurement of all 25 Lick indices from H$\delta$A to TiO$_2$. For additional details regarding observations, see S05.

Index measurements for the S05 spectra were carried out using index definitions in Table 4.1. Spectra provided sufficient wavelength coverage to measure 25 indices, however unreliable fluxes around 4546 Å and 5050 Å from CCD defects or sky subtraction errors resulted in deviant measurements for the Fe4531 and Fe5015 indices (see S05 for details), which we therefore exclude from the S05 data.

Our second source of Galactic GC data is from Puzia et al. (2002, hereafter P02). P02 provide long-slit spectra for 12 Galactic GCs in the wavelength range $\lambda\lambda 3400 – 7300$ Å. Observations were carried out using the European Southern Observatory (ESO) 1.52-m telescope on La Silla with the Boller & Chivens Spectrograph at a spectral resolution of $\sim 6.7$ Å per pixel. Lick line-strengths are given for 25 indices measured and calibrated using both the Trager et al. (1998) and Worthey (1994) index definitions. These data will be discussed further in Section 4.3.2. See P02 for more details regarding observations and line-strength measurements.

4.3.1 Multiple observations

The combined dataset used for this analysis includes spectra for 42 unique GCs with 75 observations in total. P02 contains no duplicate spectra, however S05 include multiple observations and aperture extractions for several GCs. In order to assemble a more coherent sample, analyses have been limited to a single observation for each GC in each study. In the case of multiple spectra we use those observations which are best fit for the majority of SSP models (i.e. most indices fit with the lowest $\chi^2$).
4.3. Galactic GC spectral data

For GCs with multiple aperture extractions (NGC 6284, NGC 6342, NGC 6441, NGC 6528, NGC 6624 and NGC 7078) we have used the extraction that includes a wider spatial region than just the FWHM of the slit profile as these, generally, give a better fit. We find the deviation in parameters derived from fits across multiple observations to be small (±0.015, ±0.031 and ±0.038 dex in log age, [E/Fe] and [Z/H] respectively), and consequently excluding them from our analysis has little effect on our overall conclusions.

4.3.2 Calibration to the Lick/IDS system

As discussed in Section 4.1 the general method for calibrating observations to the Lick/IDS system involves obtaining spectra of stars in the Lick standard library and using these to calculate line-strength offsets. Such calibrations have been carried out for the P02 dataset, however S05 observed Jones library (Jones, 1998) standard stars which, owing to the slightly limited spectral coverage of the Jones library (λλ 3820 – 5410 Å with a gap from 4500 Å to 4780 Å), only allow for the calibration of at most 17 Lick indices. In an effort to include as many indices as possible in our SSP model fitting, we have instead chosen to calibrate the S05 dataset using the 11 GCs it shares with P02.

P02 provide Lick indices measured using both the Worthey (1994, hereafter W94) and Trager et al. (1998, hereafter T98) passband definitions. The differences between W94 and T98 index definitions are the result of refinements to the wavelength solution of the original Lick/IDS library spectra and constitute 1.25 Å to 1.75 Å shifts in index definitions. Central indices (Hβ to Fe5406) were unaffected by this adjustment as their original definitions were calculated using more finely calibrated template spectra (W94).

Because of the index adjustment made by T98, their index definitions are the most appropriate for use on properly wavelength calibrated data; index and pseudo-continuum passbands will fall on the correct spectral features. For this reason the “correct” index definitions to use for the P02 data are from T98, however concerns have been raised with regards to the calibration of these index measurements to the Lick/IDS system. Specifically, P02’s W94 measurements were calibrated using index values published by the Lick group, while their T98 indices were calibrated using indices re-measured from the published spectra (D. Thomas & C. Maraston...
Further examination of the P02 data shows large offsets between their W94 and T98 measurements, even for indices whose passband definitions remain the same between W94 and T98.

In light of these inconsistencies we have performed calibrations of the S05 data using both the W94 and T98 index definitions. Indices were measured on the S05 spectra using both the W94 and T98 passband definitions and calibrated using the corresponding data from P02. This method of Lick calibration introduces a greater uncertainty in our calculations than if Lick standard stars were used. We have therefore adjusted our index errors accordingly, including the rms scatter about the mean offsets for the common GCs and the rms quoted in P02 for their own calibration to the Lick system (from their Tables 3 and D1) in our overall error estimates. The final errors we adopt for this calibration are shown in Appendix A, Table A.1.

For the remainder of this work we show fits to the W94 calibrated data for TMK04 and LW05 based models to avoid the uncertainties in P02’s calibration of their T98 data, discussed above. All relevant figures have been reproduced using the T98 calibrated data for comparison and are shown in Appendix B.

### 4.3.3 Vazdekis 2007 models

Data fit to the V07 models do not require the same Lick/IDS calibrations as data fit to the TMK or LW based models as they are not based on the Worthey (1994) fitting functions, using instead an independent and well calibrated stellar library. With this in mind, the S05 data were broadened to the Lick/IDS resolution using the methods described previously and indices were measured using the T98 index definitions. No additional calibration was performed.

In order to fit the P02 data to the V07 models, we have used the coefficients given for the Lick calibration of their data measured using T98 definitions (P02’s Table 3) to effectively “de-calibrate” the indices given in their Table C1. This results in indices measured using T98 passband definitions on smoothed, flux calibrated spectra.

For reference we include index-index comparisons for common GCs in P02 and S05 for the three different calibrations discussed above in Appendix A.
4.4 Galactic GC fits using SSP models

Having detailed the models and data used, we now turn to a discussion of our fitting technique. We have chosen to adopt the $\chi^2$-fitting method discussed by Proctor et al. (2004a), involving the simultaneous $\chi^2$-minimisation of as many indices as possible in order to maximise use of the available data and break the age-metallicity degeneracy. This technique has been used previously to determine ages and metallicities of GCs (Proctor et al., 2004a; Beasley et al., 2005; Pierce et al., 2003, 2006), and has been shown to produce more robust results than most individual index comparisons. The method involves the $\chi^2$-minimisation of measured spectral indices against a grid of SSP indices corresponding to different metallicities, ages and $\alpha$-element abundances. Indices which deviate significantly from the best fit ($\sim 3\sigma$) may be removed and the fits recalculated. This process can be continued until no more deviant indices are present and a stable fit is established. The fits produced by this method are robust against single deviant indices and calibration errors, and allow for the reliable identification of trends across multiple data sets.

The iterative fitting and clipping of indices involved in this multi-index technique makes easy the identification and omission of indices that are deviant for a majority
Chapter 4. Lick indices and the stellar populations of Galactic GCs

of the GC spectra. The NaD index, for example, is known to suffer heavily from interstellar absorption, and so exhibits large variations across the data sets when fit; we have therefore excluded this index from all fits. As is commonly the case in GCs, we find that residuals to best fits of the CN and Ca4227 indices follow a pattern suggestive of nitrogen enrichment (CN1 and CN2 show positive residuals, while Ca4227 shows a negative residual; e.g. TMB03, Proctor et al. 2004b). Rather than fit nitrogen as an independent parameter (e.g. TMB03), we have simply excluded these indices from the fitting procedure.

For most of the S05 spectra, measurements of the Fe4531 and Fe5015 indices were inhibited by “deviant fluxes” in their index bands, attributed to poorly subtracted sky lines or CCD defects. Both Fe4531 and Fe5015 have been excluded from all fits to the S05 spectra (see S05 for more details).

As discussed by Proctor et al. (2004a) the Fe5015 index showed large deviations between the P02 and CBR98 data sets, which are possible symptoms of the inconsistencies in conversion to the Lick/IDS system mentioned in Section 4.3. Again, since there is no absolute way to account for these deviations, the Fe5015 index was excluded from fits to the P02 data. Taking all of these effects into account, we are left to conduct fits using 20 indices for the P02 data, and 19 indices for S05.

Table 4.3 gives the details of the fits, showing the total number of times that each index was clipped for a given model set. Ca4455 was found to be very deviant in the LW05 and TMK04 models and can be interpreted as a problem in calibrations to the Lick/IDS system, as fits to the V07 models (un-calibrated data) do not show the same deviations. For all 6 model sets the C4668 index is particularly deviant, perhaps due in part to its extreme carbon sensitivity (the adopted enhancement pattern leaves carbon solar scaled). We found the Hβ index to be particularly aberrant in fits to V07 models, and so this index has been removed from all fits to V07 (both P02 and S05 data).

In Fig. 4.3 we show the mean deviations for our best fits of each index, for each set of models. Fits to models using H02 enhancements (TMK+H02, LW+H02 and V+H02) are shown as filled circles and fits to KMT05 enhanced models (TMK04, LW+KMT05 and V+KMT05) are show as open squares. Enhancement methods give qualitatively the same fits (to within a fraction of the errors) for a given model set. Comparing the quality of fit between LW05 or TMK04 and V07, one sees the
4.5. Comparison of SSP derived parameters with literature

In this Chapter we have so far discussed the measurement ages, metallicities and $\alpha$-element abundances for Galactic GCs using several stellar population models. By doing this, we are able to compare the SSP derived parameters to those determined using other methods (i.e. CMDs or resolved stellar spectroscopy) and assess the validity of SSP determinations. Establishing the reliability of these SSP predictions is vital as these models are frequently applied to extragalactic sources (galaxies and GCs) for which alternative age, metallicity and $\alpha$-element abundance determinations are not available. It is important to note that we have therefore conducted fits to

![Figure 4.3: Mean deviations of each index for each model set. Indices clipped in the iterative process described in Section 4.4 are not included. Circles and open squares represent fits to H02 and KMT05 enhanced models respectively. For V07 based models H$\beta$ was found to be particularly deviant and excluded from all fits to these models. It is shown here for comparison only.](image)

The benefit of fitting to models based on a well calibrated stellar library, in this case MILES, reflected in the reduced deviations seen for most indices.

In all subsequent figures, fits to TMK+KMT05 models are shown as open symbols plotted behind the parameters derived using TMK04 models, which are shown as filled symbols. This is done for comparison only, and analyses are carried out using TMK04 models results.

4.5 Comparison of SSP derived parameters with literature

In this Chapter we have so far discussed the measurement ages, metallicities and $\alpha$-element abundances for Galactic GCs using several stellar population models. By doing this, we are able to compare the SSP derived parameters to those determined using other methods (i.e. CMDs or resolved stellar spectroscopy) and assess the validity of SSP determinations. Establishing the reliability of these SSP predictions is vital as these models are frequently applied to extragalactic sources (galaxies and GCs) for which alternative age, metallicity and $\alpha$-element abundance determinations are not available. It is important to note that we have therefore conducted fits to
age, metallicity and α-element abundance simultaneously, rather than assuming an old age (e.g. Maraston et al. 2003; TMB03), in order to duplicate the way in which these models are frequently used for extragalactic sources.

Fig. 4.4 shows model grids of H\textbeta vs. [MgFe] for TMK04, LW05 and V07. GC data from S05 and P02 are overplotted. From Fig. 4.4, both TMK04 and LW05 models fit the data reasonably well, with the largest deviations generally at intermediate metallicities (−1.0 ≤ [Z/H] ≤ −0.5) where horizontal branch morphology becomes increasingly uncertain (see Section 4.5.5). The comparison of V07 models to data is less encouraging, as the data lie well below the grids at nearly all metallicities. This is consistent with our findings from the χ² fits, namely that the H\textbeta index is particularly deviant when compared to other indices.

At the low metallicity end, we see that models differ in their coverage of the observed data. However, as stellar libraries become extremely sparse at these low metallicities, the observed variability is not unexpected. In all cases data are consistent, within errors, with the models, which is important to our fitting procedure as stable, accurate fits are difficult to obtain for GCs whose index values fall outside the modelled range.

Having briefly looked at the base models, we now turn to a discussion of the ages, metallicities and α-element abundances derived using these SSP models.
4.5. Comparison of SSP derived parameters with literature

A direct comparison between TMK04, LW05 and V07 models is not straightforward, as each have handled metallicity in a slightly different way. TMK04 present their models in terms of $[Z/H]$ (total metallicity), having accounted for the abundance pattern of stars used to construct their SSP models (e.g. Wheeler et al., 1989), and so the values of $[Z/H]$ and $[E/Fe]_\text{SSP}$ measured using their SSPs can be used without any adjustment. In contrast, LW05 models are supplied as a function of $[\text{Fe/H}]$. As LW05 models do not, as published, account for varying $\alpha$-element ratios at $[\text{Fe/H}] \leq 0$, these models carry with them an implicit enhancement, $[\alpha/\text{Fe}]_\text{local}$, equivalent to the local stellar abundance pattern (i.e. $[\alpha/\text{Fe}] = 0.3$ for $[\text{Fe/H}] \leq -1.0$; $[\alpha/\text{Fe}]$ decreasing from 0.3 to 0.0 as $[\text{Fe/H}]$ increases from $-1.0$ to solar; $[\alpha/\text{Fe}] = 0.0$ for $[\text{Fe/H}] \geq 0.0$). This pattern must be accounted for in our measurements, in addition to the enhancement $[E/\text{Fe}]_\text{SSP}$ that we measure from our own enhancement.

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\[ [E/\text{Fe}] \] is used to describe the measured enhancement, as it represents an enhancement of N, O, Mg, Ca, Na, Si and Ti as opposed to any single element.
calculations (see Section 4.2.2). For LW05 models, \([Z/H]\) is then calculated with Eqn. 4.3 using our measured \([Fe/H]\) and \([\alpha/Fe] = [\alpha/Fe]_{\text{local}} + [E/Fe]_{\text{SSP}}\).

The V07 models provide yet another variant, being published as a function of \([Z/H]\), but do not include varying \(\alpha\)-element ratio calculations. Since the \([Z/H]\) we measure already includes the local stellar abundance pattern, and our additional enhancement calculations are applied at constant total metallicity \([Z/H]\), we can calculate \([Fe/H]\) in the same way as LW05, using Eqn. 4.3 and \([\alpha/Fe] = [\alpha/Fe]_{\text{local}} + [E/Fe]_{\text{SSP}}\).

Compounding these modelling differences is the uncertainty of the Zinn and West (1984, hereafter ZW84) GC metallicity scale used by Harris (1996). While ZW84 is generally quoted as \([Fe/H]\), it is based on measurements made by Cohen (1983) using the average of the Mg triplet (\(\sim 5175\) Å), 5270 Å and 5206 Å Fe blends. The output of a particular SSP is therefore coloured by assumptions made as to what the metallicities of Harris (1996) actually represent, i.e. iron abundance, \([Fe/H]\), or overall metallicity \([Z/H]\)). This ambiguity is magnified by evolutionary tracks and stellar libraries which may or may not have made additional assumptions as to the nature of ZW84 \([Fe/H]\) values.

In light of these ambiguities, in Fig. 4.5 we show \([Fe/H]\) measurements from Harris (1996) plotted against the most closely related metallicity indicator from each of the models. For TMK04 and V07 models, this is \([Z/H]_{\text{SSP}}\), however for LW05 this is \([Fe/H]_{\text{SSP}}\). This represents a fundamental difference in what the models are measuring, and should be kept in mind when these models are applied to spectra. This difference is likely due to the several factors mentioned above, however it does not prevent a qualitative comparison of these models. In fact all model variants shown in Fig. 4.5 find metallicities (either \([Z/H]_{\text{SSP}}\) for TMK04 and V07 or \([Fe/H]_{\text{SSP}}\) for LW05) that are in good agreement with the CMD metallicities from Harris (1996), regardless of enhancement method. Looking more closely at the offsets and scatters for each panel in Fig. 4.5 (\(\Delta\) and \(\sigma_{\text{rms}}\) respectively in the upper left corners), the TMK04 and TMK+H02 models give the tightest relations (i.e. lowest \(\sigma_{\text{rms}}\)), albeit with a slightly larger offset from the one-to-one line than LW05 based models. V07 models do not seem to follow the one-to-one line as closely as the other 4 models, generally showing larger offsets and scatters than either of the other two models.
4.5. Comparison of SSP derived parameters with literature

Figure 4.6: Zinn and West (1984) scale ages from De Angeli et al. (2005) plotted against SSP derived ages, the dotted line in this case representing the oldest age in each model set. Symbols represent P02 (squares) and S05 (circles). Numbers in the upper left corner represent the mean offset from the one-to-one line (dashed) and the $\sigma_{\text{rms}}$ scatter about that offset, error bars signify a 1$\sigma$ deviation on our SSP fits.

Figure 4.6: 

4.5.2 Age

While the range of Galactic GCs ages is quite small ($\sim$ 2 Gyrs), a comparison of SSP age predictions to literature is still useful in evaluating their reliability. In Fig. 4.6 we show such a comparison, with CMD determined ages from De Angeli et al. (2005, hereafter D05) plotted against SSP ages. Average ages are 10.74$\pm$1.84, 9.38$\pm$1.82 and 11.70$\pm$3.60 Gyrs for TMK+H02, LW+H02 and V+H02 models respectively; for models using KMT05 enhancement, mean ages are 10.78$\pm$1.63, 9.60$\pm$1.79 and 11.47$\pm$3.16 Gyrs.

Models based on V07 SSPs do a comparatively poor job of GC age prediction, finding mean offsets from D05 ages and scatters about these offsets ($\Delta$ and $\sigma_{\text{rms}}$ in the upper left corner of each panel in Fig. 4.6) significantly larger than either TMK04 or LW05 based models. Modelling uncertainties in the age-sensitive Balmer lines initially seemed the likely culprit for these large deviations, however an examination of the H$\delta$ and H$\gamma$ indices did not show a significant offset (i.e. as is observed in the H$\beta$ index for these models; discussed in Section 4.4). As an additional test to
this, fits to V+H02 and V+KMT05 were conducted with all Balmer lines omitted (HδA,F, HγA,F and Hβ), however no significant change was observed, i.e. ages were still found to be abnormally high with large scatter. As these age deviations are present in many indices (i.e. more than just the age sensitive Balmer lines), it seems that either data need some additional calibration to be properly fit to V07 models, or an additional calibration of the models themselves is needed.

TMK04 and LW05 based models do a good job of reproducing D05 ages, both finding reasonably small mean offsets (Δ < 1 Gyr). LW+KMT05 models do the best quantitative job of reproducing the CMD ages of D05, giving both the smallest mean offset (Δ = −0.057) and scatter (σ_rms = 1.544), however there are several important caveats to this age analysis.

Firstly, differing upper age limits for each of the models (15, 12 and 17 Gyrs for TMK04, LW05 and V07 respectively; dotted lines in Fig. 4.6) likely play some role in the apparent agreement or disagreement of SSP ages with literature values. Most notably, fits to LW05 based models find several GCs with ages equivalent to the upper limit of the models, whereas in fits to TMK04 derived models, all GC ages are fit as opposed to being assigned the maximum available value.

It should also be noted that differences in modelling, especially evolutionary tracks, can affect the age comparisons shown in Fig. 4.6. While Lick indices should not be affected by the particular set of evolutionary tracks used (Maraston et al., 2003), varied handling of α-element abundance ratios will influence the agreement between SSP and CMD derived ages. Both De Angeli et al. (2005) and LW05 use α-enhanced isochrones (Cassisi et al., 2004 and Kim et al., 2002), and so the good agreement in their predicted ages could be a result of this. Conversely, both TMK04 and V07 models use solar scaled evolutionary tracks, which have been shown to produce slightly older age estimates than α-enhanced isochrones of a similar metallicity (Salasnich et al., 2000).

In addition, the CMD ages of D05 are subject to uncertainties in their absolute calibration, being similarly based upon model isochrones. The ages shown in Fig. 4.6 should therefore be viewed as measuring the relative agreement of two difference methods of age measurement, CMD vs. spectral, rather than a comparison of absolute ages.
4.5. Comparison of SSP derived parameters with literature

4.5.3 α-element abundance

The ability of SSP models to accurately measure α-element abundances is of great interest as it can give an indication of formation timescales in galaxies. Measurements of enhancement using SSPs, $[\text{E/Fe}]_{\text{SSP}}$, are shown in Fig. 4.7 plotted against $[\text{Mg/Fe}]$, $[(\text{Ca+Ti})/\text{Fe}]$ and $[(\text{Mg+Ca+Ti})/\text{Fe}]$ from Pritzl et al. (2005). The agreement between Pritzl et al.’s $[\text{Mg/Fe}]$ and $[\text{E/Fe}]_{\text{SSP}}$ is poor, likely owing to the inclusion of additional elements in the SSP enhancement $[\text{E/Fe}]_{\text{SSP}}$. Perhaps not surprisingly, both $[(\text{Ca+Ti})/\text{Fe}]$ and $[(\text{Mg+Ca+Ti})/\text{Fe}]$ from Pritzl et al. (2005) relate more closely to $[\text{E/Fe}]_{\text{SSP}}$. From Fig. 4.7, we see that KMT04 and LW+H02 are able to best reproduce the enhancement values of Pritzl et al. (2005), with $[(\text{Mg+Ca+Ti})/\text{Fe}]$ being the best fit while TMK+H02, V+KMT05 and V+H02 appear to underpredict GC element abundances.

We find mean $[\text{E/Fe}]$ values of $0.12 \pm 0.08$, $0.28 \pm 0.11$ and $0.24 \pm 0.06$ for TMK+H02, LW+H02 and V+H02 respectively. Models using KMT05 enhancement calculations produce higher $[\text{E/Fe}]_{\text{SSP}} = 0.28 \pm 0.13$, $0.37 \pm 0.12$ and $0.22 \pm 0.12$. All models, with the exception of TMK+H02, produce mean $[\text{E/Fe}]_{\text{SSP}}$ values consistent with literature findings of a constant α-element abundance of $[\text{E/Fe}] \simeq 0.3$ (e.g. Gratton et al., 2004).

To further examine model enhancement predictions, in Fig. 4.8 $[\text{E/Fe}]_{\text{SSP}}$ is plotted against the same SSP metallicity indicators as Fig. 4.5 ($[Z/H]$ for TMK04 and V07, $[\text{Fe/H}]$ for LW05). The shaded region in Fig. 4.8 represents the range covered by field star data from Pritzl et al. (2005, their Fig. 4). This abundance trend with metallicity$^4$ is generally attributed to the increased influence of Type Ia SNe at later times when higher metallicity stars formed, and so it is not surprising that GCs formed at a similar epoch (i.e. metallicity) are found to follow this same α-enhancement pattern. At higher metallicities, i.e. $[\text{Fe/H}] > -0.5$, evidence for GCs exhibiting the same α-enhancement “down-turn” as field stars is less certain, however this is largely due to the small number of high-metallicity GCs relative to lower metallicities.

With regards to the SSPs fit here, TMK04, LW+H02 and V+H02 most closely

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$^3$[α/Fe] from Pritzl et al. (2005)

$^4$This trend is generally shown as a comparison with [Fe/H], however here we have plotted $[\text{E/Fe}]_{\text{SSP}}$ against the independently determined metallicity measure for each model.
Figure 4.7: SSP derived values of [E/Fe] plotted against high resolution element abundances from [Pritzl et al. (2005)]. Models and symbols are the same as in Fig. 4.5. Error bars signify a 1σ deviation on our SSP fits and ±0.1 dex for the high-resolution [$\alpha$/Fe] values.
4.5. Comparison of SSP derived parameters with literature

Figure 4.8: Comparison of fitting results for TMK04, LW05 and V07 based models. Symbols are the same as in previous figures. The shaded region shows the range of abundances observed in field stars from Pritzl et al. (2005). GCs with best fits at the minimum SSP metallicities are not shown.

match the observed field star abundance pattern. LW+KMT05 models seem to over-predict enhancements at all metallicities (as evident from the mean $[\text{E/Fe}]_{\text{SSP}} = 0.37$), while TMK+H02 greatly under-predict enhancement at low metallicities and are inconsistent with the field star pattern. All KMT05 enhanced models show some deviation at low metallicities, either over-predicting (i.e. TMK04 and LW+KMT05) or under-predicting (i.e. V+KMT05) enhancement. The variation seen in Fig. 4.8 between TMK04 and LW+KMT05, which find higher $[\text{E/Fe}]_{\text{SSP}}$ at low metallicities, and V+KMT05, which find lower $[\text{E/Fe}]_{\text{SSP}}$ at low metallicities is a result of the V07 models being offset from the data (as seen in Fig. 4.4). These deviations, however, are accompanied by increasing error distributions and so are roughly consistent with the bulk of the data. This will be discussed in more detail below.

Houdashelt et al. (2002) vs. Korn et al. (2005) enhancement

As previously mentioned, one marked difference between the KMT05 and H02 enhanced model sets is the tendency for KMT05 enhanced models to show odd enhancement behavior at low metallicities, be it the increased $[\text{E/Fe}]$ values at low metallicities in the TMK04 or LW+KMT05 models or the abnormally low $[\text{E/Fe}]$ values in V+KMT05 models.

The primary difference between the KMT05 and H02 enhancement calculations is the inclusion of metallicity dependent index sensitivities by KMT05. In their calculations, KMT05 found that indices at low metallicities are relatively insensitive
to variations in $\alpha$-element abundance. This insensitivity means that all of the SSP grid lines “pinch” together at low metallicities, resulting in indices that may be only slightly enhanced in line-strength relative to $[E/Fe] = 0.0$ being measured as having elevated enhancement (as is the case in both TMK04 and LW+KMT05 models) and increased error distributions (e.g. V+KMT05).

To test that the primary difference between H02 and KMT05 enhanced is, in fact, the added metallicity dependence rather than an overall shift in enhancement calculation between H02 and KMT05 we have constructed two new sets of models (using LW05 and TMK04) using the $[Z/H] = 0.0$ index sensitivities from KMT05 applied at all metallicities, making them comparable to H02 enhanced models. When we compare ages, metallicities and $[E/Fe]$ values between these models and their H02 enhanced counterparts (TMK+H02 and LW+H02) we find that differences are of order an interpolation step ($\pm 0.025$ dex in log age and metallicity, $\pm 0.03$ dex in $[E/Fe]$). Deviations between KMT05 and H02 models, then, are almost entirely due to the metallicity dependence added by KMT05.

4.5.4 Age-metallicity relation

The age-metallicity relation (AMR) for Galactic GCs is well established and shows that Galactic GCs are generally old (e.g. Salaris and Weiss 2002, Beasley et al. 2005; Puzia et al. 2005; D05). D05 have most recently examined the AMR of Galactic GCs using HST imaging and found that very low metallicity GCs ($[\text{Fe/H}] \leq -1.4$) are old ($\sim 11$ Gyrs) with very low scatter in their ages (0.06 Gyrs) however, at intermediate metallicities, GCs show considerably more variety in their ages, ranging from 7.5 to 11 Gyrs.

While the precision of SSP age measurements is not fine enough to delineate between slight variations in age (our general uncertainty is $\sim 2$ Gyrs), it is of interest to test whether SSP models can reproduce the overall trend of uniform, old GC ages. In Fig. 4.9 we plot the AMR as derived from each of the SSP models.

Models based on TMK04 produce AMRs that reveal an odd trend of increasing age towards higher metallicity. It should be noted, however, that age determinations at the lowest metallicities are highly uncertain due to possible variations in the horizontal branch morphology. As a result, while there is a suggestion of a positive AMR slope, the data are consistent with a uniformly old GC system. TMK04
4.5. Comparison of SSP derived parameters with literature

Figure 4.9: [Fe/H] vs. age as derived from our SSP fitting. Symbols and models are the same as in previous figures. The dotted line represents the maximum age for a particular SSP.

especially does an excellent job of reproducing a generally old GC population, finding only one GC younger than 8 Gyrs.

LW+H02 and LW+KMT05 model fits show GCs consistently old at metallicities [Fe/H] < −1, however they have a high metallicity “tail” towards younger ages. CMD age determinations for these highest metallicity GCs, NGC 6528 and NGC 6553, suggest that their actual ages are old (11 – 13 Gyrs, Zoccali et al. 2002; Feltzing and Johnson 2002) and consistent with the rest of the Galactic GC system. Comparing LW05 based models with TMK04, we note that TMK04 does not appear to have the same problem at high metallicities, finding ages for NGC 6528 and NGC 6553 consistent with CMD determinations. Errant age measures from LW05 based models could be indicative of issues with this particular model set at higher metallicities, but we are unable to comment in more detail on the quality of fits at higher metallicities due to a lack of data points. At metallicities [Fe/H] ≤ −0.4 the LW+H02 model is in excellent agreement with CMD based AMRs (e.g., De Angeli et al., 2005).

V07 based models have difficulty in producing an AMR consistent with the known GC AMR (e.g., D05). This is almost certainly due to the age determina-
Figure 4.10: TMK04 SSP grids for blue (solid lines) and red (dashed lines) horizontal branch morphologies. P02 (circles) and S05 (squares) GC data overplotted.

4.5.5 Horizontal branch morphology

Balmer line indices (H$\delta_A$, H$\gamma_A$, and H$\beta$) are particularly sensitive to the presence of hot stars, becoming weaker as temperatures decrease. This lends to their use as age indicators as the decrease in main-sequence turnoff luminosity, and therefore temperature, associated with an aging stellar population is echoed strongly in the measured Balmer line strengths. However as older populations are considered (> 10 Gyr), the increased presence of hot horizontal branch (HB) stars causes Balmer line strengths to increase, leading to an age degeneracy at low metallicities, with very old stellar populations appearing young.

The modelling of these HB morphologies is particularly difficult, as the interplay of contributing effects (e.g. mass-loss, metallicity, dynamical effects etc.) is not known well enough to be modelled in detail (i.e. based purely on theory). Modelling varying HB morphologies, then, has been done primarily via prescriptive methods. Maraston and Thomas (2000) find that a mass-loss prescription is able to reproduce the strong Balmer lines found in old elliptical galaxy populations, as well as the trends of increasing H$\beta$ line strengths in low-metallicity Galactic GCs.

Of the SSP models used here, only TMK04 allow for a variation of HB morphology.
in their models, supplying two sets of empirically calibrated Balmer line indices (\(H\delta_{A,F}, H\gamma_{A,F}\) and \(H\beta\)), one each for Red and Blue HB morphology (see Maraston and Thomas 2000 for details). In Fig. 4.10 we show a comparison of the BHB (solid lines) and RHB (dashed lines) grids supplied by TMK04. This figure illustrates the need for a consideration of variable HB morphology, especially at intermediate metallicities where hot horizontal branch stars begin to cause large variations in Balmer line strengths.

In an effort to better quantify the HB effects in our results, we have performed a second set of fits to the RHB models of TMK04 using the same techniques described in Section 4.4. In Fig. 4.11 we show the difference between age, metallicity and \(\alpha\)-element abundance derived using BHB and RHB models plotted against the GC horizontal branch ratio (HBR) from Harris (1996) and Zoccali et al. (2000). Since the HBR is based purely on numbers of stars in a given branch\(^5\) it provides an excellent, independent means of determining HB morphology.

The first thing to note in Fig. 4.11 is that GCs with HBRs > 0.9 are almost entirely blue, and so have been excluded from the statistics shown in the bottom

\[\text{HBR} = \frac{B-R}{B+V+R}\]
left of each panel. As the RHB modelling in TMK04 is limited to Balmer line indices, it is not surprising that the changes seen in \([Z/H]\) and \([E/Fe]\) as a result of this modelling are small. In particular, the offsets for both are dominated by the scatter. Ages are most strongly affected by varying HB morphology in the TMK04 SSP models, however even mean offset for these (\(\sim 0.11\)) is of order the error for our age determinations (\(\sim 0.1\)).

While the results of this comparison do show that HB morphology is important to individual indices (e.g. \(H\beta\) in Fig. 4.10), it does no appear that it greatly affects the properties that we derive using the multi-index fitting technique. Most importantly, the offsets that we see as a result of varying the HB modelling are not large enough to significantly change the results of our analyses.

### 4.6 Conclusions

In this Chapter we have used Lick indices measured from the integrated spectra of Galactic GCs as a testbed for SSP model predictions of age, metallicity and \(\alpha\)-element abundances. The multi-index \(\chi^2\)-minimization technique adopted here has allowed us to measure GC stellar population parameters consistent with published values, even in situations where data are poorly fit in a single index-index space.

We have shown metallicity determinations to be robust with respect to both the models used and enhancement calculations applied. We note that differences in the construction of models can lead to a fundamental difference in the absolute metallicities they predict, however the relative comparison of metallicities is only minimally affected. With regards to GC metallicity scale, \([Z/H]\) measurements from TMK04 and V07 models are mostly closely related to CMD \([Fe/H]\) from \(\text{Harris (1996)}\). LW05 models, on the other hand, predict \([Fe/H]\) measurements which are more closely related to the metalicities of \(\text{Harris (1996)}\). This does not affect our conclusions, however this variability in absolute value is an important caveat to applying these models to extragalactic GC systems and galaxies.

Age determinations using either TMK04 or LW05 based models are reliable for the old GCs of the Milky Way. V07 models have difficulty in recovering age measurements consistent with their CMD derived counterparts, finding GCs that are too old with significant scatter. The scatter in GCs measured using V07 models is
worrisome, and likely related to both the unknown calibration of these models to known stellar populations (see e.g. Section 4.2.1) and the uncertainty in calibrating data to these models.

Of the models tested here, only TMK04 models provide measurements of $\alpha$-element abundances at all metallicities without an *ad hoc* addition of enhancement calculations. We have shown, however, that a relatively simplistic application of Lick index sensitivity calculations from either KMT05 or H02 allows the recovery of reasonable $\alpha$-element abundances (i.e. consistent with the literature) from almost any SSP model. This holds particularly true for the LW+H02 models shown in Fig. 4.8, which appear to reproduce the observed field star $\alpha$-element abundance trend remarkably well.

HB morphology is an important consideration for globular clusters as blue horizontal branch stars can dramatically affect the age sensitive Balmer line indices. However, in spite of these Balmer line variations, we find changes in SSP determined ages as a result of varying HB morphology (i.e. blue or red HB models) are relatively small for the majority of GCs when using the multi-index $\chi^2$ fitting method. Determinations of metallicity and $\alpha$-element enhancement are relatively robust to changes in HB morphology, a key result for extragalactic GC studies where direct determinations of HB morphology are unavailable.

Finally, it is worth considering the implications of our findings here for application of SSP models to extragalactic systems, both GCs and galaxies. We can conclude that measurements of metallicity using SSPs are reliable for a broad range of metallicities, regardless of $\alpha$-element abundance, model or HB morphology. This should also be the case when models are applied to galaxies with the caveat that the ages, metallicities and $\alpha$-element abundances derived for complex stellar populations using SSP models are strictly the luminosity-weighted mean.

Although the Galactic GCs in our sample cover a wide range in metallicity ($-2.28 \leq [\text{Fe/H}] \leq -0.04$ dex), they cover only a limited parameter space in age and $\alpha$-element abundance (the mean age of our GCs is $10.23 \pm 0.83$ Gyrs from De Angeli et al. 2005, and $[\alpha/\text{Fe}] = 0.30 \pm 0.09$ dex from Pritzl et al. 2005), a significant disadvantage for application to galaxies, which are likely to span a significant range in both $\alpha$-element abundance and age.

In the $\alpha$-element and age parameter space GCs do cover, $\alpha$-element abundance
determinations for Galactic GCs are robust to model variations in the high-metallicity regime. Below \([Z/H] \sim -1.0\), \(\alpha\)-element abundances can vary significantly depending on the base model used and enhancement calculations applied. This is problematic for studies of extragalactic GCs but less so for massive galaxies as their metallicities are typically super-solar. Integrated spectral measurements of \(\alpha\)-element abundance in dwarf galaxy systems may suffer the same strong model dependence as our Galactic GC sample due to their similarly low metallicities.

Due to the limited range probed by Galactic GCs, i.e. almost exclusively old, age determinations for SSPs are uncertain. This uncertainty is compounded by the fact the \(\chi^2\) method of Proctor et al. (2004a) used here has yet to be thoroughly tested on integrated stellar populations with young, independently-confirmed ages such as those found in the Galactic GCs of Pal 12 and Terzan 7, or resolvable extragalactic GCs in the Magellanic Clouds and M67. Nevertheless, for old objects, e.g. GCs or massive elliptical galaxies, age measurements should be reliable as this regime is thoroughly covered by the resolved-star Galactic GC observations analysed in this Chapter. As discussed above, we are unable to comment on the quality of age determinations in young objects due to their absence from our test sample.
Stellar populations of NGC 5044 group galaxies

While the majority of our understanding of the variation of galaxy properties with environment hinges on large photometric surveys, an alternative approach is the use of spectral absorption features as detailed tracers of galaxy stellar populations. In many ways spectral analyses provide a vastly increased level of detail for determining paths of galaxy formation and evolution relative to photometry, however they are often hindered by smaller sample sizes and relatively high observational expense. Nevertheless, absorption-line studies have met with great success in tracing the stellar populations of individual galaxies (e.g. Proctor et al., 2004a; Thomas et al., 2005; Sánchez-Blázquez et al., 2006; Peletier et al., 2007; Spolaor et al., 2008), galaxy clusters (e.g. Smith et al., 2007, 2008; Trager et al., 2008; Smith et al., 2009) and large survey samples (e.g. Gallazzi et al., 2006; Jimenez et al., 2007; Proctor et al., 2008).

To date, spectroscopic studies with a particular focus on environment have primarily made use of cluster galaxy populations. Kuntschner (2000) used a magnitude limited sample of early-type galaxies in the Fornax cluster to study trends in age and metallicity, finding that they show tight scaling relations between their metal-line strengths and line-of-sight velocity dispersion. Caldwell et al. (2003) used a sample of nearby early-type galaxies in the Virgo Cluster, as well as a field-galaxy sample, to probe galaxy stellar populations to low masses ($\sigma < 100$ km s$^{-1}$). Caldwell et al. (2003) found a greater intrinsic scatter in the properties of low-mass galaxies,
however they made no particular effort to examine the spatial distribution of galaxy populations within the Virgo Cluster. In similar work, Smith et al. (2008) and Smith et al. (2009) have examined the stellar populations of dwarf galaxies in the Coma Cluster and Shapley supercluster, in both instances finding that the scaling relations of low-mass populations are generally consistent with the relations of higher-mass E and S0 galaxies, although with the same increased scatter noted by Caldwell et al. (2003). In the case of Coma, Smith et al. (2009) find a radial dependence of both age and metallicity, where galaxies at larger projected radii are both younger and higher metallicity, suggestive of recently quenched star formation among galaxies entering the Coma cluster outskirts and consistent with earlier spectral studies of Coma cluster galaxies (Caldwell et al., 1993; Mobasher et al., 2001; Carter et al., 2002).

These studies, however, only serve to probe the rare high-density cluster environment, neglecting the much more common group environment. In an attempt to fill this gap, here we undertake a detailed spectroscopic study of the galaxy population in the NGC 5044 group with the aim of describing galaxy evolutionary histories and reconstructing the formation history of the group as a whole. The greatly improved, spectroscopically defined sample described in Section 3 has allowed us to characterise the dynamical state of the group, which we find to be relaxed from a combination of X-ray and dynamical indicators. Here, we turn our focus to analysing the stellar populations of galaxies in this redefined group with a focus on establishing the details of galaxy evolution in the context of the group environment.

The structure of this Chapter is as follows: In Chapter 5.2 we discuss the measurement of Lick index absorption features and their interpretation in terms of age, metallicity and $\alpha$-element abundance. In subsequent sections we discuss the stellar population properties of NGC 5044 group galaxies both as an independent galaxy sample (Section 5.3), and in the context of their place in the group as a whole (Section 5.4). In Section 5.5 we describe the distribution of emission-line properties for NGC 5044 group galaxies. In Section 5.6 we discuss our stellar population findings in relation to the dynamical description of the group presented in Chapter 3 as well as their relevance to the formation and evolution of the NGC 5044 group and galaxies therein.
5.1 Lick indices and calibration to the Lick/IDS system

As discussed in the previous Chapter, we use Lick absorption indices to characterise the stellar populations of our NGC 5044 group galaxies. As before these measurements have been carried out using the index definitions given by Trager et al. (1998) and Worthey and Ottaviani (1997) (given in Table 4.1). We omit from our Lick index measurements Fe5782, NaD, TiO$_1$ and TiO$_2$ as these fall in the wavelength range of the AAOmega dichroic where sensitivity is decreasing rapidly. Index measurement and velocity dispersion corrections are carried out as described in Section 4.1.

5.1.1 Lick/IDS system calibration

In order to calibrate our index measurements to the Lick/IDS system, Lick standard star observations were carried out at the beginning of each observing night (see Table 2.1 for details of stars observed). Index measurements for AAOmega data are then adjusted based on a comparison of published Lick standard star indices and our stellar observations. The mean offsets found for each index are listed in Table 5.1 along with their associated rms error.

We are unable to calibrate 6dFGS data in the same way as AAOmega data, and so we generate two sets of indices for 6dFGS galaxies: the first using the corrections provided in Table 5.1 and the second with no correction. We refer the reader to Section 5.2.1 for a comparison of the properties derived using these two sets of indices for overlapping 6dFGS and AAOmega galaxies.

5.1.2 Index errors

Results from the multi-index $\chi^2$ minimisation technique we use depend strongly on robust error determinations for our index measurements. In order for these fits to be reliable an accurate representation of index errors is crucial, but notoriously difficult to obtain for spectral observations.

Proctor et al. (2008, hereafter P+08) have recently used spectra from the 6dFGS DR1 (Jones et al. 2004) to measure ages and metallicities in a large sample of galax-
Chapter 5. Stellar populations of NGC 5044 group galaxies

Table 5.1: Lick index corrections for AAOmega data and their associated errors.

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<th>Index</th>
<th>Offset</th>
<th>( \sigma_{\text{rms}} )</th>
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ies using Lick indices. In estimating their index errors, P+08 have used duplicate observations of the same galaxy (from overlapping survey regions) to calculate the rms scatter in their Lick index measurements at a given S/N. The rms value was then fit as a function of S/N using the form \( \sigma_{\text{rms}} = a/(S/N + b) \), where \( a \) and \( b \) are constants, which was then used to calculate representative errors for the rest of the galaxy sample based on their S/N. This method not only encapsulates redshift and velocity dispersion errors, but also errors resulting from sky subtraction, fibre flat-fielding and throughput calibration that are nearly impossible to quantify in individual fibre observations.

Here we adopt a similar strategy to P+08 and exploit the composite nature of our final spectra by re-measuring indices on individual observations, of which there are 12 and 35 observations each for bright and faint galaxies respectively. We then adopt the \( \sigma_{\text{rms}} \) for these repeat measurements as an accurate representation of the stochastic errors in our sample (i.e. Poisson noise, sky-subtraction etc). In Fig. 5.1 we show how the H\( \beta \) index error derived in this manner varies as a function of S/N for the galaxies in our sample, and for comparison we also show the line describing index errors as derived by P+08 for 6dFGS DR1 data. Error curves for all indices are shown in Appendix C.

For our AAOmega data the total adopted index error is a combination of this
random error, the $\sigma_{\text{rms}}$ associated with conversion to the Lick/IDS system (Section 5.1.1) and the index broadening due to errors on velocity dispersion and recession velocity measurements (Section 2.2.1). For 6dFGS data we adopt the recession velocity and velocity dispersion errors as discussed in Section 2.2.1 as well as the index errors as a function of S/N derived by P+08.

### 5.2 Stellar population models and fitting

Having discussed the details of our index measurement on these data we now turn to the task of interpreting these measurements in terms of the stellar population parameters they describe. In the previous Chapter we used Galactic GCs to gauge the reliability of SSP models in determining known population parameters. The relevant findings from that Chapter to our current task of interpreting our galaxy data are summarised below:

(i) **Metallicity estimates.** Metallicity determinations are relatively model independent, notwithstanding systematic variations in the absolute value of their measurements, and reliable for the broad range of sub-solar metallicities probed by Galactic GCs.
(ii) \([Z/H]\gtrsim -1.0\) dex. \(\alpha\)-element abundance estimates are model independent for metallicities greater than about one-tenth solar. Age estimates in this regime are uncertain, but when using TMK04 or LW05 models ages are generally consistent with similar measurements from resolved stellar populations for old stellar systems (i.e. GCs).

(iii) \([Z/H]\lesssim -1.0\) dex. \(\alpha\)-element abundance estimates at metallicities from one-tenth solar and below are strongly model dependent. Various models are capable of measuring \(\alpha\)-element abundances anywhere from solar up to a factor of five above solar, and therefore must be used somewhat cautiously. Ages measured in the low-metallicity regime are comparable to high-metallicity estimates in terms of their reliability in matching the ages determined from resolved observations.

Of the models examined in Chapter 4, Thomas et al. (2004) and Lee and Worthey (2005) + Houdashelt et al. (2002) models (TMK04 and LW+H02 respectively) provide the most reliable recovery of properties in Galactic GCs. While LW+H02 models appear to be superior in their determination of \(\alpha\)-element abundances as a function of metallicity, the necessity of using our \textit{ad hoc} application of variable
abundance calculations makes them less preferable for use on galaxy data. Finally in practical terms, the TMK04 models are widely used in literature for studies of extragalactic systems. In order for our data to be comparable to these studies we therefore adopt the Thomas et al. models for the remainder of this work. We refer the reader to Chapter 4 for details on the construction of these models. As a reminder, the variable abundance ratios included by TMK04 consider N, O, Mg, Ca, Na, Si and Ti as enhanced elements and, while these fall outside a strict definition of $\alpha$-elements, we will hereafter refer to enhancement measures from the TMK04 models as $\alpha$-element abundances or $[\alpha/\text{Fe}]$.

As stated previously, we adopt here the multi-index $\chi^2$ minimisation technique of Proctor et al. (2004a), simultaneously fitting as many Lick indices as possible. Similar to the fitting methodology applied in Chapter 4 our goal is to obtain a stable fit between galaxy data and the TMK04 models; we therefore adopt a similar iterative approach in our fitting. As a first step we perform a fit using as many indices as our data allow, which for AAOmega and 6dFGS data is generally between 18 and 21. In subsequent iterations indices deviant from the best-fit solution at the 5, 4 and 3$\sigma$ levels are clipped. A final manual inspection of the fit is then carried out to ensure that stable fits have been attained and ensure that indices have not been over- or under-clipped as a result of poor error estimates.
Figs. 5.2 and 5.3 show the mean deviation of indices from the best fit model for AAOmega and 6dFGS data respectively. Galaxies free of emission are generally fit very well by the TMK04 models and we clip at most 2 indices from any given galaxy. Emission-line galaxies are significantly more difficult to fit, however the emission-cleaned spectra output from GANDALF (see Section 5.5.1) result in a large improvement to the overall quality of fits for AAOmega data (Fig. 5.2b,c) and slight improvement for 6dFGS data (Fig. 5.3b,c).

Final errors on our stellar population measurements are estimated using a Monte Carlo method which re-samples the best-fit model convolved with our observed index errors. These error estimates represent our best attempt to quantify the random error contribution to our measurements, however there is an additional systematic error present in the models themselves which we do not account for (see, e.g., Conroy et al., 2009). In Table 5.2 we provide the parameters for galaxies in our spectroscopic sample including stellar masses, $B$-band mass-to-light ratios, ages, metallicities and $\alpha$-element abundances.
Table 5.2: Spectroscopic parameters for confirmed NGC 5044 group galaxies. Columns are as follows: (1) Galaxy identifier, (2) right ascension (J2000), (3) declination (J2000), (4) velocity dispersion, (5) stellar mass, (6) stellar mass-to-light ratio in the B-band, (7) age in units of log Gyrs, (8) iron abundance, (9) $\alpha$-element abundance.

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Chapter 5. Stellar populations of NGC 5044 group galaxies

Figure 5.4: Comparison of metallicity ([Z/H]), α-element abundance and age for the 6 overlapping 6dFGS and AAOmega galaxies with S/N > 12. Open (red) and filled (black) circles represent galaxies with and without emission lines. Dashed lines in each panel represent equality. Parameters for 6dFGS data are shown with no applied correction to the Lick/IDS system (see Section 5.1.1).

The 6dFGS and AAOmega spectra used in this work can only be used to derive luminosity-weighted ages, metallicities and α-element abundances. This is important to any subsequent analyses as these luminosity-weighted values are particularly affected by small centralised bursts of star formation and may not be representative of the global galaxy properties. In addition, because of aperture size differences between AAOmega and 6dF (2.1′′ vs. 6.7′′; 0.3 kpc vs. 0.9 kpc at the distance of NGC 5044) we expect some variation in the derived stellar population parameters due to both sampling differences and the presence of radial gradients, predominantly in metallicity.

5.2.1 Comparison of AAOmega and 6dFGS galaxies: agreement and aperture effects

In Fig. 5.4 we show the comparison of stellar population parameters derived for overlapping AAOmega and 6dFGS galaxies. In this comparison we have used indices measured from 6dFGS data with no Lick/IDS system correction applied. Using indices adjusted using the AAOmega Lick/IDS system correction gives similar results, but with an increase in scatter. We therefore use uncorrected 6dFGS indices for the remainder of this work.

Of particular interest here is the comparison between galaxy properties sampled using the different fibre apertures of AAOmega and 6dF. Perhaps the most obvi-
ous trend is observed in metallicity, which is also the most robust of our stellar population measurements. 6dFGS galaxies show a systematic offset towards lower metallicities of $\sim 0.1$ dex, consistent with observations that the majority of galaxies possess negative gradients in metallicity (i.e. galaxies are more metal-poor at larger radii, e.g. Sánchez-Blázquez et al. 2007; Brough et al. 2007).

Comparisons of $\alpha$-element abundances and ages are considerably more scattered than metallicity, indicative of the increased difficulty in their measurement. Broadly, we expect the larger fibre aperture of 6dF to yield older ages, particularly for galaxies with recent or currently ongoing star formation as these bursts are (generally) centrally concentrated. We find this to be the case for half of the 6dFGS galaxies, but the other half scatter to younger ages with considerable uncertainty. As these galaxies are just above our adopted S/N cut, we consider these measurements to be highly uncertain rather than representative of a real trend in the data. We expect the variation in aperture size between AAOmega and 6dF to have little systematic effect on the measured $\alpha$-element abundances, as observed gradients in $[\alpha/\text{Fe}]$ are both weak and variable. In Fig. 5.4, $\alpha$-element measurements using AAOmega data are consistently higher than those from the 6dFGS data. Again, this is most likely a S/N effect as the small dynamic range of $\alpha$-element abundances makes their determination difficult in low S/N data.

Motivated by the comparisons in Fig. 5.4 and the discussion above, in forthcoming sections we consider galaxy metallicities to be robust for both the 6dFGS and AAOmega samples. Age and $\alpha$-element abundances for 6dFGS galaxies can be used to give a rough indicator of stellar population trends at larger group-centric radii, but we will refrain from using them to make any specific judgements due to the large uncertainty in their relationship to AAOmega data.

5.3 Galaxy properties

5.3.1 Stellar population parameters versus stellar mass

Before attempting to place our observed galaxy population in the context of the NGC 5044 group environment, we first examine the properties of galaxies independent of their particular place in the group. In Fig. 5.5, we show how our measured
Figure 5.5: Relationship between stellar population properties and stellar mass (see Section 5.3.1). Filled (black) and open (red) symbols represent passive and emission-line galaxies (see Section 5.5.1), with circles and triangles delineating galaxies measured using AAOmega and 6dFGS spectra, respectively. Errors bars represent 1-sigma deviations estimated using the Monte Carlo technique described in Section 5.2.
5.3. Galaxy properties

Figure 5.6: Comparison of stellar masses derived using both $B$- and $K$-band photometry, with filled (black) and open (red) symbols representing passive and emission-line galaxies respectively. The *dashed* line represents equivalence between the two mass estimates.

Ages, metallicities and $\alpha$-element abundances vary with stellar mass. Stellar masses have been computed using the GALEXEV stellar population synthesis models of Bruzual and Charlot (2003; hereafter BC03). Here we use BC03 models constructed using the “Padova 1994” isochrones (see BC03 and references therein) and stellar initial mass function (IMF) of Chabrier (2003). Using our derived central ages and metallicities, we then extract the appropriate $B$-band mass-to-light ratio (M/L) from the BC03 models.

Before continuing on to our analysis of properties as they vary with stellar mass, it is important to first consider the possible systematics present in our GALEXEV-based mass estimates. Stellar masses based on $B$-band magnitudes are known to be heavily biased by young (blue) stellar populations relative to mass estimates based on near-infrared (NIR) magnitudes. A sub-sample of our NGC 5044 group galaxies have both $B$- and $K$-band magnitudes available, and so we are able to roughly analyse the systematics induced by our choice in photometry. In Fig. 5.6 we show the comparison of $B$- and $K$-band mass estimates for the 30 galaxies with both
B- and K-band photometry available. From Fig. 5.6 it is immediately apparent that our use of B-band photometry has led to a general underestimate of stellar mass relative to estimates from the NIR, which becomes particularly pronounced for emission-line galaxies.

In terms of our stellar population parameters this underestimate in stellar mass can be most easily understood in terms of a general underestimate of luminosity-weighted stellar age; that is, the stellar age measured from our central spectral observations is younger than suggested by the global photometric data by between ∼0.1 and 0.7 dex (estimated as the age difference required for the two mass estimates to agree for passive and emission-line galaxies, respectively). This is consistent with a picture where the majority of recent star formation is centrally concentrated, and therefore strongly influences our central measurements of luminosity-weighted ages (see also age discussion below). An additional caveat, however, is that our stellar-population parameters are estimated from absorption lines concentrated in the B-band, and therefore these estimates are most appropriately paired with B-band photometric data. Unfortunately we lack the spectral coverage to compare NIR stellar population estimators (such as the CaII triplet) with our Lick/IDS system measurements.

In general, the offset between B- and K-band mass estimates is small in the passive galaxy population, and so conclusions drawn about the non-emission-line galaxy population of the NGC 5044 group will change little regardless of the mass estimate used. Results for emission-line galaxies are obviously increasingly uncertain due to their ongoing star formation and young central stellar populations, which manifests as an underestimate of masses based on B-band photometry. For the remainder of this thesis we use B-band-based estimates of galaxy stellar mass as it facilitates the inclusion of a larger galaxy sample in our analysis, however with a mind that these mass estimates are likely to be lower limits, particularly in emission-line galaxies.

Of the three stellar population parameters measured and shown in Fig. 5.5, metallicity shows the strongest correlation with mass, spanning more than two decades with a scatter of ∼0.26 dex. The general tightness of the mass–metallicity relation as determined from both emission- and absorption-line analyses is well known from large samples such as the SDSS (e.g. Tremonti et al. 2004; Gallazzi
5.3. Galaxy properties

Figure 5.7: Mass–metallicity relation for galaxies spanning a broad range of environments. Filled circles, open circles and open squares represent data from the NGC 5044 group, Local Group and Shapley supercluster respectively and include only non-emission-line galaxies. Errors for the Local Group data are taken as the average error quoted in Woo et al. (2008) of 0.17 and 0.2 dex for stellar mass and metallicity. Errors on NGC 5044 group and Shapley supercluster metallicities have been estimated using the Monte Carlo technique described in Section 5.2.

et al., 2006), however our data probe this relation an order of magnitude lower in both mass and metallicity. We see evidence for increased scatter among emission-line galaxies (∼ 0.39 dex for emission-line galaxies vs. ∼ 0.23 dex for passive galaxies), which could be indicative of “contamination” from recently formed stellar populations or an effect of errors in our mass estimates. We note, however this could equally be related to the quality of emission-line corrections in these galaxies.

An interesting question related to the mass–metallicity relation is the degree to which it depends on environment. While a detailed analysis of this dependence requires a comparison of galaxies at fixed stellar mass in a range of environments, even a qualitative comparison of the mass-metallicity relation in several different environments should allow identification of any gross systematic deviations. To this end, we have selected a comparative sample of galaxies, both at higher and lower masses, in two other environments, the Local Group and the Shapley supercluster. Data for Local Group dwarf galaxies are taken from the compilation of Woo et al. (2008), who provide stellar masses, derived using the colour-M/L relation of Bell and de Jong (2001), and average [Z/H] from individual red giant branch stars observed in
these galaxies. Metallicities for a sample of galaxies in the Shapley supercluster have been calculated using Lick line index measurements from Smith et al. (2007) and the fitting methods described in Section 5.2. Stellar masses for these galaxies have been estimated as described above, using $B$-band magnitudes from Smith et al. (2007). A comparison of the mass–metallicity relation for these three samples is shown in Fig. 5.7. In this figure, metallicity estimates for Shapley supercluster galaxies have had additional offset of +0.15 dex applied to account for the different physical aperture size between NGC 5044 and Shapley observations (0.3 kpc vs. 1.9 kpc respectively) assuming an average metallicity gradient of $-0.25$ dex per dex, e.g. Sánchez-Blázquez et al. (2007). Data shown in Fig. 5.7 form a remarkably uniform mass–metallicity sequence over roughly six orders of magnitude in galaxy stellar mass, despite the widely varied environments sampled. Furthermore, apart from the obvious differences in stellar mass range, the data suggest that environment is likely playing only a small role in establishing the mass–metallicity relation, consistent with recent results from the SDSS (e.g. Mouchine et al., 2008; van den Bosch et al., 2007).

Interpretations of the mass–metallicity relation generally focus around decreasing star-formation efficiency at low mass, which can suitably explain the trends observed in galaxies (e.g. Tremonti et al., 2004; Savaglio et al., 2005; Gallazzi et al., 2006) and is reproduced in hydrodynamic simulations of galaxy evolution (e.g. Brooks et al., 2007). In this interpretation of the mass–metallicity relation we expect to see low-mass galaxies trend towards lower $\alpha$-element abundances as the relationship of $\alpha$-element abundance to supernovae timescales, namely SNII versus SNIa contributions, provides leverage in differentiating between rapid, high-efficiency star formation and ongoing, low-efficiency star formation (e.g. Terlevich and Forbes, 2002; Thomas et al., 2005).

Examining the observed relation of $[\alpha/\text{Fe}]$ with mass in Fig. 5.5, we find considerable scatter, particularly in galaxies with emission. The majority of this scatter results from increasingly large index errors at low S/N (see Appendix C), but there is also a systematic effect related to our fitting of low-mass, and hence low-metallicity, data. The TMK04 model grids “pinch” together at low $[Z/H]$, making the discrimination of $[\alpha/\text{Fe}]$ increasingly difficult (see Section 4.5.3 and Fig. 4.8). As a result, while we appear to observe significant scatter in the $[\alpha/\text{Fe}]$ measurements
5.3. Galaxy properties

of low-mass galaxies, which would generally indicate significant variation in star-
formation histories, we are unable to draw any strong conclusions from these data. If we restrict ourselves to galaxies with \( \log M_\ast \gtrsim 8.5 \), then our data exhibit a weak positive correlation of \( \alpha \)-element enhancement with mass at the \( \sim 95 \) percent level, consistent with the interpretation of the mass–metallicity relation as indicative of star-formation efficiency, discussed above.

Age estimates show a clear offset between emission-line and passive galaxies, unlike either metallicity or \( \alpha \)-element abundance. The mean stellar age of emission-line galaxies is \( \sim 3.6 \) Gyrs, relative to \( \sim 9.1 \) Gyrs for passive galaxies. We must, of course, interpret these age measurements with caution as they are strictly luminosity-weighted averages within our fibre apertures. Emission-line galaxies show a trend of younger central ages towards increasing mass, significant at the \( \sim 2\sigma \) level, which we believe to be largely driven by aperture effects and the centrally concentrated nature of star formation. Analyses of central stellar populations in conjunction with global photometric measurements allow one to constrain the relative fraction of mass contained in central starbursts, which has been found to be of order 10 percent for a range of galaxy masses (e.g. P+08). If we consider the fact that the fraction of galaxy light sampled by AAOmega’s 2” aperture varies by more than an order of magnitude from the brightest to faintest sources in our sample, then the stellar population measurements for our most massive galaxies are dominated by any central star formation, while in smaller galaxies we sample a growing fraction of the underlying, older stellar population.

The passive sample of galaxies seems to separate into two sub-samples: one with relatively uniform, old ages (\( \gtrsim 9 \) Gyrs), and a second population with relatively young central ages. This younger sub-sample almost certainly represents galaxies which have more recently undergone bursts of star formation and are now fading to older apparent ages. One possible cause for this population could be recent, gas-rich mergers which would serve to drive down central age measurements (e.g. Kauffmann, 1996). In this scenario we would expect to see these star-formation bursts accompanied by a decrease in the ratio of \( \alpha \)-element abundance to iron as new generations of stars form from increasingly metal-enriched gas, however the \( \alpha \)-to-iron ratios for these galaxies are consistent with the bulk of the passive galaxy population.
Figure 5.8: Projections of the fitted plane to age, mass and metallicity. Symbols are the same as Fig. 5.5. Dashed lines represent equality and are shown for reference.

To summarise, the ages, metallicities and $\alpha$-element abundances of galaxies in the NGC 5044 group are consistent with properties found in larger galaxy samples. The tight mass–metallicity relation and its interpretation as a sequence of star-formation efficiency is consistent with our measurements of $\alpha$-element abundance, although the trend of elemental abundance with mass appears relatively weak in these data.

5.3.2 The age–mass–metallicity relation

The comparison of galaxy ages, metallicities and $\alpha$-element abundances described in the previous section demonstrates the close relationship between metallicity and stellar mass, but it should also be considered that more complex relationships between multiple stellar population parameters and mass may exist. For example, in a study of local early-type galaxies [Trager et al. (2000)] found that their elliptical galaxies were described by two separate two-dimensional relations in four-dimensional space: a plane described by the linear combination of $\log t$, $\log \sigma$ and $[Z/H]$, and a relationship between $[\alpha/Fe]$ and $\log \sigma$ such that more massive galaxies have higher values of $\alpha$-element enhancement. [Smith et al. (2009)] found a similar relation between age, mass and metallicity for dwarf galaxies in the Coma cluster, noting in particular an increase in scatter at low masses.

Motivated by recent comparisons suggesting a tight relationship between the properties of galaxies at a fixed stellar mass (e.g. van den Bosch et al., 2008), we fit the plane described by our data for age, mass and metallicity such that
5.3. Galaxy properties

Figure 5.9: Age–metallicity relation for NGC 5044 group galaxies. Symbols are the same as in Fig. 5.5. Lines of constant stellar mass are shown for \( \log M_* = 8, 9, 10, 11 \). Error bars are the 1-sigma errors determined from Monte Carlo simulations (see Section 5.2).

\[
\log M_* = \alpha [Z/H] + \beta \log t + \gamma, \tag{5.1}
\]

using a least-squares fitting method and minimising residuals orthogonal to the plane. The best-fitting parameters for these data result in a plane such that \( \alpha = 1.83 \pm 0.46, \beta = 1.41 \pm 0.79 \) and \( \gamma = 9.00 \pm 0.61 \). In Fig. 5.8 we show projections of this best-fit plane in stellar mass, \( M_* \), metallicity, \( [Z/H] \), and age. There is a clear separation between passive and emission-line galaxies about the fitted plane, which is driven primarily by the difference in mean age of the two populations and evident in Fig. 5.8. The separation between these two populations is inconsistent with being an effect of the age–metallicity degeneracy in our fits, which primarily moves galaxies along the trends in Fig. 5.8. If we consider fits to the emission- and non-emission-line galaxies separately, both populations show a similar dependence on stellar mass; the offset between these two populations is dominated by a varying age–metallicity relation. Low-mass galaxies in our sample exhibit an increase in scatter about the fitted plane relative to their high-mass counterparts, in agreement with the observations of Smith et al. (2009).
The projections shown in Fig. 5.8 are helpful to examine the distribution of galaxy parameters relative to one another, but are somewhat difficult to interpret physically. In Fig. 5.9 we show a more standard projection of the plane in terms of age and metallicity, where dashed lines represent the age–metallicity relation at fixed stellar mass as derived from the best-fit plane discussed above.

If we naively interpret the distribution of galaxy ages and metallicities shown in Fig. 5.9, then there is little evidence for a relationship between central galaxy age and metallicity; galaxies formed at a similar time in the early universe exhibit a spread in metallicity of two or more dex. However, our fits in the age–mass–metallicity plane suggest that this is a flawed conclusion. While it is true to say that there is no clear age–metallicity trend when considering our total sample of galaxies, subsamples of data in narrow mass bins (one or two orders of magnitude) suggest that galaxies with older central ages are more metal poor than centrally young galaxies, supporting evolution of the mass–metallicity relation over time (e.g. Kobulnicky and Phillips, 2003; Brooks et al., 2007; Lamareille et al., 2007; Maiolino et al., 2008).

5.3.3 Predicted vs. observed colours

Up to this point we have used the BC03 models to derive M/L, and hence mass, for our galaxies, however it is important to establish the extent to which these SSP models accurately describe the properties of our sample galaxies. To undertake this comparison we have supplemented the $B$- and $K$-band photometry discussed in Section 2.2.3 with $B - V$ and $g - i$ colours for a subsample of NGC 5044 group dwarf galaxies presented by Cellone (1999) and Cellone and Buzzoni (2001; 2005; S. Cellone 2008, private communication). Predicted colours are calculated using the BC03 models and measured ages and metallicities. Comparisons of these predictions to our observed colours are shown in Fig. 5.10.

Galaxies lacking in emission show relatively good agreement with the predicted BC03 colour for their age and metallicity. This serves as an excellent confirmation in the reliability of M/L estimates for these galaxies which, to some extent, can be seen from the tightness of the mass-metallicity relation in Fig. 5.3. The scatter in colours of emission line galaxies is considerable, and the causes of this are likely to be twofold: firstly, we are sampling fundamentally different regions with our spectroscopy.
5.4 Global properties and galaxy distribution

We have so far examined general trends in the galaxy population of the NGC 5044 group in their own right. We now turn to a more general discussion of the distribution of galaxy properties within the group.

5.4.1 Stellar population trends with radius

By combining semi-analytic models for star formation and galaxy evolution with recent, large-scale \textit{N}-body simulations such as the Millennium Simulation (Springel et al., 2005), recent theoretical work has made great strides in predicting the distribution of galaxy properties in massive structures like groups and clusters. As an example, De Lucia et al. (2006) found that the luminosity-weighted age, metallicity and photometry. Whereas this has a negligible effect for passive galaxies, the centrally concentrated star-formation in our emission galaxies means that the colours we predict should be, and indeed generally are, bluer than the observed “global” photometry. In addition, stellar population parameters derived for our emission-line galaxies are the most uncertain, which leads to a greater uncertainty in both our measurements of ages and metallicities and hence a corresponding uncertainty in their predicted colours. Overall, however, the above comparisons suggest that our galaxy data are reasonably well described by the BC03 models.
Chapter 5. Stellar populations of NGC 5044 group galaxies

and stellar mass fall with increasing distance from the cluster centre in their models, out to the virial radius. Given the hierarchical formation scenario favoured in current ΛCDM models these results are not surprising; those galaxies in the highest density regions form first, and subsequent generations of galaxies accreted by the cluster are distributed with radius according to the redshift at which they become cluster members (e.g. Gao et al., 2004). It should be noted, however, that there is considerable scope for the interpretation of projected cluster-centric distance as an indicator of accretion time to be confused by three-body interactions which can eject bona fide members to beyond the virial radius (see e.g. Ludlow et al., 2009).

In light of these predictions, we are motivated to examine the radial distribution of stellar populations in the NGC 5044 group. Galaxies residing in groups and clusters for more than a dynamical time should undergo some degree of mass segregation due to the increasing efficiency of dynamical friction with total galaxy mass. In apparently relaxed groups and clusters, such as NGC 5044, we expect any such segregation to be readily apparent. In Chapter 3 we examined the distribution of dwarf and giant galaxies in the NGC 5044 group using $B$-band magnitudes as a simple discriminator between low- and high-mass systems but found no significant evidence for differing radial distributions of these two sub-populations. Here, we are able to refine this analysis using the stellar masses derived from the BC03 models.

In the upper panels of Fig. 5.11 we show the distribution of stellar mass, age, $\alpha$-element abundance and metallicity in fixed radial bins. In the lower panels we show the radial distribution of galaxies in bins of stellar mass, age, $\alpha$-element abundance and metallicity. This figure includes only those galaxies within 500 kpc of the group centre (roughly two-thirds the group’s virial radius) as this is approximately the region observed uniformly with our new AAOmega observations, and thus less prone to spurious, selection-induced trends.

Focusing first on the distribution of properties in fixed radial bins, we find no significant differences in the mean values for age or $\alpha$-element abundance (shown by vertical dashed lines in the top panels of Fig. 5.11). Data show some evidence for a deviation in mean galaxy stellar mass and metallicity, and a Kolmogorv-Smirnov (KS) test confirms that metallicities in the inner 150 kpc of the group are inconsistent with being drawn from the same distribution as either of the outer two radial bins at the 2.5 sigma level. Despite the apparent offset in mean stellar mass, a KS test
5.4. Global properties and galaxy distribution

Figure 5.11: The radial dependence of various properties of galaxies in the NGC 5044 group. Top panels show the distribution of stellar mass, age, $\alpha$-element abundance and metallicity in three different radial bins of $R < 150$ kpc, $150$ kpc $\leq R \leq 250$ kpc and $R > 250$ kpc (solid orange, green and blue hatched regions respectively). Vertical dashed lines show the mean of each bin. Lower panels show the radial distribution of galaxy properties in three separate bins of stellar mass, age, $\alpha$-element abundance and metallicity, where bins have been selected to contain roughly equal numbers of galaxies.

does not find galaxies in the inner group region to have a significantly different mass distribution relative to other radial bins.

Turning to the radial distribution of galaxy properties (Fig. 5.11 lower panels), a KS test finds that both low-mass and low-metallicity galaxies ($\log M_\star < 8.8$ and $[Z/H] < -0.7$ dex) exhibit radial distributions that are different to their higher mass and metallicity counterparts. Qualitatively, these differences are evident in Fig. 5.11 by the clear lack of galaxies from the lowest mass and metallicity bins in the inner 100 kpc of the group centre. The fact that we see this segregation in both mass and metallicity is expected from the tight correlation between these two quantities in our data; the converse holds true for the lack of peculiar distributions in age and $\alpha$-element distributions given their lack of a strong correlation with mass.

In order to investigate the relationship between mass, metallicity and radius further, in Fig. 5.12 we show galaxy metallicities plotted against their group-centric radii, where galaxies have been separated into three separate mass bins. This figure serves as a visual confirmation of the mean offset of galaxy metallicity observed within $\sim 150$ kpc in Fig. 5.11 and also shows that this trend is due primarily to a lack of low-mass galaxies — and hence low metallicity — from the inner 100 kpc of the group. Finally, Fig. 5.12 suggests that there are no strong radial trends in
Previous work by Mathews et al. (2004, hereafter M+04) using the NGC 5044 group catalogue of FS90 has noted a similar lack of low-luminosity galaxies in the inner group region. Assuming dwarf galaxies act as tracer particles in the group potential, M+04 compared the cumulative number distribution of dwarf galaxies to the predicted surface mass distribution of a Navarro-Frenk-White (NFW) dark matter profile (Navarro et al., 1995, 1996, 1997), finding that the NGC 5044 group falls well below the NFW prediction inside \( \sim 300 \text{kpc} \). M+04, and later Faltenbacher and Mathews (2005, hereafter FM05), offer two explanations for this apparent central deficit of dwarf galaxies. M+04 argue that a lack of dwarf galaxies could be tied to a low survival rate of low-mass galaxies entering the NGC 5044 group halo at high redshift \( (2 \leq z \leq 6) \), or due to suppression of star formation in low-mass galaxies as a result of AGN or outflow activity from the central galaxy. The follow-up work by FM05 showed, using a simple dynamical model, that tidal disruption and dynamical friction could also be responsible for the apparent lack of dwarfs at small radii. In their model, low-mass galaxies approaching the central group potential could be strongly disrupted or destroyed.

Our sample has allowed us to refine the NGC 5044 group membership used by M+04, and we find that substituting our spectroscopically confirmed sample for the
photometric sample of FS90 does not significantly alter the conclusions of M+04; there still appears to be a deficit of dwarf galaxies at low projected radii ($\lesssim 300$ kpc). M+04 suggest that, as a result of low dwarf galaxy survival rates at high redshifts, there should be a relative lack of old, low-mass galaxies in the group. The data presented in Fig. 5.11 do not suggest any such trend in galaxy ages, with low-mass galaxies appearing similar in mean age to their high-mass counterparts (see also Figs. 5.5 and 5.9). In addition, the M+04 scenario would suggest that, relative to massive galaxies, low-mass dwarf galaxies should be kinematically “younger” in their velocity distribution in the group. However, as shown in Section 3.4.2, we find no such evidence for kinematic segregation between high- and low-luminosity galaxies. A repeat analysis of sub-population kinematics using the stellar masses derived in this work gives a similar result, further suggesting that the scenario posed by M+04 does not describe these data in full.

Perhaps the most plausible explanation is that put forward by FM05, where the apparent central deficit of dwarf galaxies is a result of both dynamical friction and tidal disruption. In their work, FM05 find that the evolution of galaxies with total-to-stellar mass ratios of $\sim 20$ best describe the population of disrupted galaxies in the NGC 5044 group. Using the relationship between stellar mass and total baryonic mass determined from fits to star-forming galaxies in the SDSS (Baldry et al., 2008), we can use the cosmic baryon fraction, $f_b = 0.171$ as determined from the WMAP 5yr results (Komatsu et al., 2009) to estimate the total halo mass for galaxies of a given stellar mass. For the total-to-stellar mass ratio predicted by FM05 of 20, the above relation gives a corresponding stellar mass of $\log M_* \approx 8.6$. This is in agreement with the lower limit of stellar mass that we observe in the central 100 kpc of the group centre, providing support for the tidal disruption scenario of FM05.

Confirmation of this would need to come from additional deep imaging to observe the low surface-brightness intragroup light which, given the possibly large number of disrupted or destroyed dwarf galaxies, could be as much as $\sim 35$ percent of the group’s total luminosity (FM05).

\footnote{Where the NFW profile is scaled to match the cumulative galaxy distribution at $\sim 350$ kpc as in M+04}
5.4.2 Galaxies and the hot intragroup medium

The metal content of the intrachannel/intragroup medium (ICM/IGM) is directly related to the star formation histories of the galaxies via outflows and supernovae driven winds, and therefore provides a useful diagnostic of both group and galaxy evolution. Despite the presence of ongoing evolution in the stellar populations of group and cluster galaxies, observations of high redshift X-ray samples suggest that the bulk of ICM metals were already in place at $z \sim 1$ (e.g. Tozzi et al., 2003; Balestra et al., 2007) and therefore necessitate that most star formation activity and subsequent ICM enrichment takes place at early times.

Rasmussen and Ponman (2007, hereafter RP07) have used Chandra archival data to analyse the X-ray abundance properties of 15 nearby groups, including NGC 5044. From their data RP07 extract radial profiles of iron and silicon abundance in the hot IGM out to $\sim 200$ kpc in NGC 5044, facilitating a comparison between our galaxy stellar population measurements and the chemical properties of the intragroup gas. In Fig. 5.13 we plot the X-ray derived radial iron and silicon abundances along with the stellar mass-density profiles.

In their abundance analysis of hot gas in the NGC 5044 group, RP07 show that the central silicon to iron ratio is roughly solar (i.e. $[\text{Si/Fe}] \sim 0.0$), suggesting SNIa are playing an important role in enriching gas in the central group regions. While
we lack significant overlap between the X-ray profiles and our binned group profile, the slopes in both iron and silicon abundance in the intragroup gas are consistent with that of the stellar mass density between $\sim 50$ and 100 kpc. If SNIa enrichment occurred early on in the group, we would expect the silicon and iron profiles to be relatively flat with radius due to IGM mixing; the fact that we see a relatively steady decline in both silicon and iron would suggest that the SNIa enrichment has, instead, occurred primarily at late times. In clusters, the “excess” of iron in the central regions relative the rest of the ICM is normally attributed to enriched outflows from the central galaxy (e.g. Böhringer et al., 2004). In the case of NGC 5044 this remains a plausible explanation for the high central iron abundance, particularly given recent evidence for large outflows associated with NGC 5044’s central AGN (Temi et al., 2007; Gastaldello et al., 2009). We note, however, that our data are also consistent with satellite galaxies having contributed significantly towards building up the central iron peak in the group, particularly given the extended nature of the central excess, $\sim 50$ kpc, relative to the optical extent of NGC 5044 ($\sim 20$ kpc; FS90; Paturel et al., 2000; shown with black dashed line in Fig. 5.13) and the good correspondence between the radial profile of iron abundance and stellar mass-density out to beyond $\sim 100$ kpc.

In the outer regions, $R > 100$ kpc, there is evidence for a rising silicon abundance, in contrast to the iron abundance which continues to fall. While the significance of this upturn is only marginal due to its dependence on the outer-most measurement in the X-ray data, we have no reason to believe this is a spurious measurement. The observed rise in [Si/Fe] is in agreement with X-ray observations for numerous groups and clusters (e.g. Finoguenov et al., 2000; RP07) and suggests an increased contribution of SNII relative to SNIa at large projected radii and potentially significant mixing, suggesting enrichment at early times.

To explore the relation between galaxies and the intragroup medium further, in Fig. 5.14 we show the same binned X-ray abundance profiles as in Fig. 5.13, only this time overlayed on the radial galaxy trends for metallicity and $[\alpha/Fe]$ shown in Fig. 5.12. This figure clearly shows that both the IGM iron abundance and the [Si/Fe] ratio are well below the average values measured in galaxies at similar radii, despite both iron and silicon declining with radius at a similar rate to the stellar mass-density. This is consistent with the findings of Buote et al. (2004), who also
Figure 5.14: Comparison of X-ray derived silicon and iron abundance profiles (dashed lines in each panel) with the distribution of galaxy α-element abundances and metallicities. Galaxy symbols are the same as in Fig. 5.12. X-ray data have been binned for clarity.

Note the low abundance of iron in the IGM relative to the group luminosity (compared to clusters), as well as other work suggesting a high fraction of “primordial” gas in the IGM (e.g. Gibson and Matteucci [1997]; Moretti et al. [2003]).

In terms of silicon abundance, we find a surprising correlation between the rise in [Si/Fe] at \( \sim 100 \text{kpc} \) and the presence of low-mass, dwarf galaxies at similar radii. If there is a connection between these two observations, it would imply a very high contribution of SNII relative to SNIa in dwarf galaxies, as well as a significant contribution from these low-mass systems to the total gas mass of the group. Previous studies, however, have shown that, while dwarf galaxies certainly contribute to the reservoir of intragroup gas, it is most likely not significant, constituting at most 15% of the total gas mass in clusters (Gibson and Matteucci [1997]). This suggests that the connection between these observations is likely only coincidental, particularly given the relatively low IGM iron abundance outside the group core, 10% solar, and the likely sub-solar outflows from dwarf galaxies.
5.5 Emission line properties

Using the sub-sample of our NGC 5044 group with measurable emission lines, we now discuss the emission-line characteristics of our group galaxies, including star-formation rates and nebular metallicities.

5.5.1 Emission-line measurements

We identify emission-line galaxies in our AAOmega and 6dFGS samples through examination of residuals to the best fit pPXF templates used to derive recession velocities and velocity dispersions (see Section 2.2.1), and for 24 galaxies in our sample of confirmed group members we find evidence for emission in some combination of \( \text{H}\beta \), \([\text{OIII}]_\lambda 4959\), \([\text{OIII}]_\lambda 5007\), \([\text{NI}]_\lambda 5198\) and \([\text{NI}]_\lambda 5200\). While we can estimate emission-line fluxes from the residuals of our template fits, the underlying absorption in these regions is generally poorly constrained as emission contaminated lines are masked in the template fitting process.

A far more robust method is to fit for absorption- and emission-line kinematics simultaneously, which we carry out using the GANDALF software of Sarzi et al. (2006). This is an extension of the pPXF pixel fitting routine described in Section 2.2.1 which fits simultaneously a set of absorption and emission templates, eliminating errors introduced by fitting emission line residuals separately. Fits to emission lines are conducted using a set of independent Gaussian profiles whose kinematics can be varied as required. Here we treat the kinematics of nebular and Balmer-line emission separately, tying each to the kinematics of the dominant features in appropriate regions of our spectra (\( \text{H}\beta \) or \( \text{H}\alpha \) and \([\text{OIII}]_\lambda 5007 \) or \([\text{NII}]_\lambda 6583 \) for Balmer and nebular lines respectively). Our choice to fit separately the kinematics of Balmer and nebular emission lines has a negligible effect on our results as we find no galaxies with a significant kinematic difference between the two (where both are detected). There is generally good agreement between kinematics measured using pPXF and GANDALF; the largest offsets are observed in velocity dispersion, and are only significant in galaxies with strong emission lines and relatively weak continuum flux.

GANDALF also allows for spectra to be cleaned of detected emission. Here we follow Sarzi et al. (2006) and adopt an amplitude-to-noise (A/N) threshold of 4, where noise is defined as the scatter about the best-fit absorption template. As both
[NI] and Hβ emission strongly affect our Lick index measurements the removal of these lines results in a significant improvement in the quality of stellar population fits for emission-line galaxies (see discussion in Section 5.2). The approximate detection threshold of emission lines in our data can be calculated as a function of S/N using our adopted A/N and typical line broadening. If we assume a typical intrinsic line width of $\sim 30 - 50 \text{ km s}^{-1}$, then our sensitivity is $\sim 0.6 \text{ Å}$ for AAOmega data and $\sim 0.9 \text{ Å}$ for 6dFGS data at the median S/N of our galaxy data.

We use the Hα/Hβ Balmer decrement to calculate the extinction correction for our emission-line fluxes where applicable using the $R_V = 3.1$ reddening curve of Cardelli et al. (1989) and an intrinsic Hα/Hβ line ratio of 2.85 (Osterbrock, 1989). In galaxies with very low extinction the errors on our line-flux measurements can sometimes result in a negative extinction estimate. As this is clearly non-physical we adopt $E(B-V) \leq 0.01$ as an upper limit of extinction and assign this to galaxies with low or spurious (i.e. negative) extinction measurements.

In order to separate galaxies undergoing star formation activity from those with other strong ionising sources, i.e. AGN, we use a standard emission line diagnostic
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comparing the $\text{[OIII]}_{\lambda 5007}/\text{H}\beta$ and $\text{[NII]}_{\lambda 6584}/\text{H}\alpha$ flux ratios \cite{Baldwin1981}, shown in Fig. 5.15. We use two predictions to characterise the emission line flux ratios of our galaxies. The first is the theoretical maximum starburst limit calculated by \cite{Kewley2001} \textit{dashed} line in Fig. 5.15, while the second is the semi-empirical limit of pure star formation defined by \cite{Kauffmann2003} using a large sample of SDSS emission line galaxies \textit{solid} line in Fig. 5.15. These lines separate our sample into galaxies which are purely star-forming, strongly AGN or ionised by a composite source (some contribution from both AGN and star-formation), shown with circles, triangles and squares in Fig. 5.15.

NGC 5044 is known to host AGN activity \cite{Rickes2004, Brough2007} and is identified as such in Fig. 5.15, but we also identify two other group galaxies as hosts of potential AGN or other strong ionising sources: NGC 5037 (FS 068) and FS 082. The classification of these galaxies as AGN sources is supported by the available \textit{Chandra} data, in which all three galaxies are detected.

5.5.2 Star formation rate

In large samples, comparisons of galaxy properties with local environment show strong evidence for a decreasing fraction of star-forming galaxies in regions of higher projected galaxy surface density \cite{Lewis2002, Gomez2003, Poggianti2006}. Even at relatively low gas densities, such as those found in groups, recent work has shown that ram-pressure stripping can influence star-formation via depletion of a galaxy’s hot-gas reservoir \cite{Sivakoff2004, Machacek2005, Rasmussen2006, Kawata2008}. However in higher-density environments, such as the Coma cluster, \cite{Poggianti2004} have found evidence for young post-starburst galaxies preferentially located near the edges of X-ray substructures. These observations suggest that galaxy–ICM interactions may play a key role in the truncation of star formation, but may equally contribute to initiating bursts of star formation in galaxies as they encounter dense environments.

In our own data, varying fibre throughput and sensitivity make proper flux calibration of our data difficult and therefore limit our ability to derive absolute measurements of the star formation rate, SFR, using H$\alpha$ line fluxes. Instead, we use the relation derived by \cite{Guzman1997} to estimate star formation rates using $B$-band luminosity and [OII] equivalent widths, where
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Figure 5.16: Specific star-formation rate as it varies with projected distance from the group centre. Errors are indicative of the uncertainty in our EW\([\text{[OII]}]\) and \(B\)-band luminosity measurements, but do not include the systematic contribution from using \([\text{OII]}\) over \(H\alpha\) and equivalent widths as opposed to line fluxes (see Section 5.5.2).

\[
\text{SFR}(M_\odot \text{ yr}^{-1}) \approx 2.47 \times 10^{-12} L_B(L_\odot) \text{ EW}[\text{OII}].
\] (5.2)

The use of \([\text{OII]}\) instead of \(H\alpha\) introduces an additional error into the estimation of the star formation rate of order 0.2 to 0.3 dex [Kewley et al., 2004]. The relation fit by Guzman et al. (1997) to convert between \([\text{OII]}\) flux and \([\text{OII]}\) equivalent width carries with it increased uncertainty of \(\sim 0.1\) dex in the derived SFR. Given these two relatively significant error contributions, in addition to the relatively large errors in the FS90 and Paturel et al. photometry (0.5 and 0.3 dex respectively, see Section 2.2.3), we consider our star formation rates to only be proportional to the star formation activity in any given galaxy, but by no means a clear indicator of the absolute star formation rate.

In Fig. 5.16 we show the specific star formation rate for galaxies as estimated using Eqn. 5.2 in relation to their projected radius from the group centre. The star formation rates shown in Fig. 5.16 have been normalised by the galaxy stellar mass and are shown in units of \(\text{yr}^{-1}\) per \(10^9 M_\odot\). We see no clear correlation of SFR with radius, and results are similar if we consider projected galaxy density. Motivated by the possible dependence of SFR on galaxy–ICM/IGM interaction, we have also examined the star formation rate relative to a simple expression proportional to the IGM ram pressure, \(P_{\text{ram}} = \rho(r)|\vec{v}_{\text{group}} - v|^2\), where \(\rho(r)\) is the IGM density...
5.5. Emission line properties

and $|\vec{v}_{\text{group}} - v|$ is the galaxy velocity $v$ relative to systemic group velocity $\vec{v}_{\text{group}}$. Assuming that $\rho(r) \propto r^{-2}$, we then arrive at a comparison of SFR against $|\vec{v}_{\text{group}} - v|^2/r^2$, which shows a similar lack of correlation as the radial and galaxy density comparisons described above. We note that projection effects are likely having a strong effect on any of our radial SFR comparisons as we cannot properly relate our galaxy positions and recession velocities to their true position and relative motion withing the group. Nevertheless, while these data do not allow us rule out the role of interactions with intragroup gas as influencing the observed star formation in these galaxies, they seem to hint that these effects are relatively limited in this case.

An alternative possibility for triggering or enhancing star formation is through galaxy–galaxy interactions. Hydrodynamic simulations modelling gas have shown that tidal interactions can enhance or induce central star formation by driving gas from the disk to the central regions (e.g. Barnes and Hernquist, 1992; Di Matteo et al., 2007), which supports observations of enhanced star formation in close pairs of galaxies (e.g. Lin et al., 2007; Ellison et al., 2008). An examination of DSS images for the 22 galaxies with [OII] emission shows that only 2 galaxies, FS90 134 and FS90 137, exhibit clear evidence for ongoing interaction. Several other galaxies show some evidence of disturbed morphology (i.e. boxy bulges and disturbed disks), however it appears that the majority of recent star formation activity we see in the NGC 5044 group is not driven by currently ongoing galaxy–galaxy interactions.

5.5.3 Emission-line metallicity

Nebular metallicity and underlying, stellar metallicity are intimately related via star formation. The evolution of stellar metallicity (as measured by absorption features) is strictly dependent on a galaxy’s star formation history, while nebular metallicities continue to vary as previous generations of stars evolve and enrich the interstellar medium. We are therefore able to use the relative offset of emission- and absorption-line metallicities to extract information related to the last significant star formation episode. Here we use a reparameterisation of the Kewley and Dopita (2002, hereafter KD02) $R_{23}$ method presented by Kobulnicky and Kewley (2004, hereafter KK04) to derive gas-phase metallicities for a subsample of our emission-line galaxies. We exclude from this analysis galaxies exceeding the maximum starburst limit shown in Fig. 5.15 as likely hosting AGN (NGC 5044, NGC 5037 and FS 082).
To summarise briefly, the primary diagnostic used in the KD02 method is the emission-line ratio defined by

$$\log R_{23} = \frac{[\text{OII}]_{\lambda 3727} + [\text{OIII}]_{\lambda 4959} + [\text{OIII}]_{\lambda 5007}}{H\beta} \equiv x. \quad (5.3)$$

The $R_{23}$ ratio is known to be sensitive to both metallicity and the ionisation state of the gas which leads to the inclusion of a second, ionisation sensitive parameter, $O_{32}$, defined as

$$\log O_{32} = \log \left( \frac{[\text{OIII}]_{\lambda 4959} + [\text{OIII}]_{\lambda 5007}}{[\text{OII}]_{\lambda 3727}} \right) \equiv y. \quad (5.4)$$

$R_{23}$ is two-valued, and so separate relations are necessary for high- and low-metallicity branches. KK04 provide a new parameterisation of these branches such that

$$12 + \log(O/H)_{\text{lower}} = 9.40 + 4.65x - 3.17x^2$$
$$- \log(q)(0.272 + 0.547x)$$
$$-0.513x^2), \quad (5.5)$$

and

$$12 + \log(O/H)_{\text{upper}} = 9.72 - 0.777x - 0.951x^2 - 0.072x^3$$
$$-0.811x^4 - \log(q)(0.0737$$
$$-0.0713x - 0.141x^2$$
$$+0.0373x^4 - 0.058x^4). \quad (5.6)$$

The ionisation parameter $q$ is determined theoretically by KD02 using the relation between $[\text{OIII}] / [\text{OII}]$ and $q$ derived from photoionisation models, which KK04 express as a function of both $O_{32}$ and $12 + \log(O/H)$ such that
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Figure 5.17: Comparison of metallicity derived from the nebular oxygen abundance, $[Z/H]_{R_{23}}$, and stellar metallicity, $[Z/H]_{Lick}$, derived using Lick indices. The dashed line represents equality between the nebular and stellar metallicities.

$$\log(q) = \{32.81 - 1.153y^2 + [12 + \log(O/H)](-3.396 - 0.025y + 0.1444y^2)\} \times \{4.603 - 0.3119y - 0.163y^2 + [12 + \log(O/H)(-0.48 + 0.0271y + 0.02037y^2)]\}^{-1}. \quad (5.7)$$

In order to select the appropriate branch of the $R_{23}$-metallicity relation, i.e. high- or low-metallicity, we use the metallicity sensitive emission-line ratio $\log([\text{NII}]/[\text{OII}])$, adopting $\log([\text{NII}]/[\text{OII}]) \approx -1.2$ as the break between galaxies on the upper and lower branches (KD02; Kewley and Ellison 2008). Due to the dependence of the ionisation parameter on the oxygen abundance, calculations are carried out iteratively, generally requiring only several iterations to converge on a solution.

The $R_{23}$ metallicity calibrator is typically defined using emission line fluxes, however this requires spectra to be properly flux calibrated as line ratios spanning a significant wavelength range will otherwise be incorrect. An alternate approach is to use measurements of equivalent width in place of line fluxes to compute EW-$R_{23}$, which avoids the issues of flux calibration and extinction correction, but introduces
the problem of potential variation in the underlying stellar continua (particularly between old and young spectra). In a statistical sense, the variation between $R_{23}$ and EW-$R_{23}$ results in an additional error on the final metallicity determination of $\sim 0.11 \text{dex}$ \cite{Kobulnicky2003}, however in our relatively small sample where we know the underlying stellar populations vary significantly, the uncertainty between $R_{23}$ and EW-$R_{23}$ can have a potentially significant effect on our results. Considering both the wide range of spectra types and uncertain flux calibration of our data, we estimate nebular metallicities using both $R_{23}$ and EW-$R_{23}$. Since the effects of varying stellar continua and flux calibration affect emission-line metallicity measurements differently, by using both of these measurements we can assess the reliability of our conclusions.

Comparison of EW-$R_{23}$ and $R_{23}$ shows that the scatter between the two measures is $\sim 0.08 \text{dex}$, or $\sim 0.11 \text{dex}$ in terms of the final determination of $12 + \log(O/H)$ \cite{Kobulnicky2003}, which is generally less than the intrinsic error in the calibration of $R_{23}$ to nebular oxygen abundance. In our own data, the scatter between EW-$R_{23}$ and $R_{23}$ is $\sim 0.16 \text{dex}$, but this scatter is primarily driven by two galaxies with significant offsets between EW-$R_{23}$ and $R_{23}$. Excluding these galaxies the scatter on our data falls to $\sim 0.07 \text{dex}$. We therefore exclude these deviant galaxies from the remainder of our emission line analyses and consider measurements on the remaining galaxies to be reliable.

Comparison of stellar and nebular metallicities is carried out by converting nebular oxygen abundances to the implied metal mass fraction using the relation $Z \simeq 29 \times 10^{[12+(O/H)]-12}$, assuming the standard solar abundance distribution and solar oxygen abundance of $12 + (O/H) = 8.72$ \cite{AllendePrieto2001,Kobulnicky2004}. In Fig. 5.17 we show the comparison between the converted nebular metallicities and stellar metallicity. In general, derived nebular metallicities are super-solar and, in some cases, nearly 1.5 dex higher than their stellar counterparts. The relatively shallow relation between stellar and nebular metallicities is somewhat puzzling, as it implies a significantly weaker mass-metallicity relation among star-forming galaxies that is generally observed (e.g. \cite{Tremonti2004}).

It is worth considering the extent to which this offset could be due to systematics in the two methods used to calculate nebular and stellar oxygen abundance. Of the two measurements, we have shown in Chapter 4 that metallicity measure-
ments carried out using Lick indices are relatively accurate in an absolute sense, agreeing to less than 0.1 dex with alternative measurements. The absolute value of emission-line metallicities, however, is less certain. Kewley and Ellison (2008) have shown that the scatter in theoretical emission-line metallicity estimates, including the KK04 estimator, is only 0.02 to 0.05 dex and therefore errors in our emission-line metallicity estimates are dominated by systematics in the conversion between oxygen abundance, O/H, and metallicity, [Z/H]. If we consider the range of solar oxygen abundances from $Z = 0.015$ to 0.020, the change in inferred total metallicity ($[Z/H]$) in this range can be as much as $\sim 0.15$ dex.

Perhaps more importantly, it is impossible to entirely separate our emission- and absorption-line measurements given that they are intimately related to the best-fit spectrum obtained from pPXF and GANDALF (see Sections 2.2.1 and 5.5.1). From an absorption-line perspective, emission-line correction has little effect on the metallicity measured from Lick indices as prominent metal features are unaffected by emission lines in either their central- or side-bands regions. Errors on emission-line fluxes (and hence nebular metallicities) have been estimated using successive fits to the galaxy spectrum with random noise added to match the level of the best-fit continuum residual and range from $\sim 0.15$ to 0.2 dex. These errors, however, are typically random in nature and so should be unable to induce any trend in our emission-line data, instead only contributing scatter to the observed relations. In the worst case scenario, e.g. all errors correlated in such a way as to maximise the apparent offset between nebular and stellar metallicity, the above error sources are able to account for $\sim 0.40$ to 0.45 dex of offset, still leaving a factor of $\sim 10$ in metallicity offset unaccounted for in some cases.

Given this somewhat curious, and apparently robust result we are motivated to examine the relative difference between nebular and stellar metallicity as a function of other galaxy properties. In Fig. 5.18, the relative offset between nebular and stellar metallicity is plotted against galaxy stellar mass, age and $\alpha$-element abundance. The relationship between metallicity offset and stellar mass in Fig. 5.18 is driven primarily by the mass–metallicity relation and shows that the most massive galaxies have the lowest measured nebular–stellar metallicity offsets as a result of the relatively uniform, high nebular metallicities measured.

In terms of age, those galaxies with the lowest metallicity offsets also have the
youngest luminosity-weighted ages, which is consistent with the observed stellar population forming recently from gas present in these galaxies. Interestingly, while the trend of metallicity offset with age is consistent with our understanding of galaxy formation, the magnitude of this offset is large, nearly 1.5 dex in the case of the lowest-mass galaxies. This offset is difficult to explain through pure passive evolution of the stellar populations in these galaxies, i.e. through enrichment from SNII and SNIa, which in extreme cases can account for $\sim 1$ dex of metallicity increase (see, e.g. Sansom and Proctor 1998). An alternate explanation is that ongoing star formation has helped to enhance the observed gaseous metallicities through the evolution of metal-enriched stars. In this case the integrated stellar populations should also appear both younger and more metal rich in those galaxies hosting the largest nebular–stellar metallicity offsets, in conflict with the trends in Fig. 5.18. Finally, these data could be explained in a scenario where the gas reservoirs of low-mass galaxies are being preferentially depleted over high-mass galaxies, which would increase the effect of any subsequent enrichment due to supernovae.

In order to explain these observations in terms of gas removal, we require that the removal process must be more efficient in low-mass galaxies, ruling out AGN activity as a possibility due to its strong scaling with mass. Starburst outflows, primarily driven by SNII, satisfy the above stated mass dependence but would also likely affect the observed $[\alpha/\text{Fe}]$ ratio of stars formed from any remaining gas, in conflict with Fig. 5.18. Galaxy–IGM interactions such as ram-pressure stripping (Gunn and Gott, 1972) and viscous stripping (Nulsen, 1982) satisfy both the inverse mass dependence and non-preferential gas removal (i.e. gas-phase metals from SNII
and SNIa must be removed more-or-less equally) stipulated by these observations. Strictly speaking, we cannot rule out any processes from contributing to the observed galaxy processes, however our data are best explained by galaxy–IGM dominating gas removal in the NGC 5044 group.

5.6 Discussion and conclusions

In this Chapter we have undertaken a spectroscopic investigation of galaxies in the group environment, deriving stellar masses, ages, metallicities and $\alpha$-element abundance ratios for 67 of the 111 spectroscopically confirmed NGC 5044 group members described in Chapter 3. These measurements have allowed us to examine the star formation histories of these group members, both as a population in their own right and in the context of the group environment and their location in it.

The mass–metallicity relation plays a fundamental role in describing galaxy populations, and we see strong evidence of this in the overall tightness of the mass–metallicity relation in our group data over multiple orders of magnitude in stellar mass. In the context of environment, by comparing the mass–metallicity relation of NGC 5044 group galaxies with galaxies in the Local Group and the Shapley supercluster, we show that galaxies appear to form a continuous mass–metallicity relation across several orders of magnitude in system mass and spanning upwards of six orders of magnitude in galaxy stellar mass. These data argue for a relative independence of the mass-metallicity relation from environment (e.g. Maiolino et al., 2008; van den Bosch et al., 2008).

In terms of galaxy ages and $\alpha$-element abundances, we find no evidence for strong trends with galaxy mass. Our $\alpha$-element abundance data do not rule out the interpretation of star formation efficiency as the primary driver of the mass–metallicity relation. Particularly at higher stellar masses ($\log M_* \gtrsim 9$) and metallicities, where wide separation of model grids allow for finer abundance measurements, our data show hints of a trend of increasing $\alpha$-element ratio with mass, consistent with literature results (e.g. Terlevich and Forbes, 2002; Thomas et al., 2005). We have shown that the surface described simultaneously by age, mass and metallicity is vital to analyses of galaxy data spanning a broad range in mass. Most notably, mass dependence is vital to interpretation of the galaxy age–metallicity relation.
In terms of the radial distribution of galaxies, we find no apparent radial dependence in either age or $\alpha$-element abundances. A KS test finds that low-mass and low-metallicity galaxies have radial distributions inconsistent with their high-mass and high-metallicity counterparts, and an examination of this apparent difference shows that we observe no galaxies with $\log M_* \lesssim 8.9$ within $\sim 100$ kpc projected radius from the group centre. In the context of previous analyses of the NGC 5044 group, M+04 and FM05 have both noted the apparent lack of dwarf galaxies in the group’s central regions using the photometric catalogue of FS90. Our spectroscopic observations confirm that the dwarf galaxy distribution observed by M+04 and FM05 is not due to the inclusion of significant foreground or background contamination in the FS90 catalogue (see Section 3.1.1 and Fig. 3.3). Of the possible scenarios for explaining this deficit, the most plausible seems to be that dwarf galaxies are being tidally disrupted or destroyed through interactions with the group or central galaxy potential. Our data are consistent with the simulations of FM05 in their prediction of total-to-stellar mass ratios for disrupted galaxies of $\sim 20$, corresponding to $\log M_* \approx 8.6$. Deep wide-field imaging is required to confirm this conclusion, as the models of FM05 predict stars from the disrupted population of dwarf galaxies to contribute nearly 35 percent of the total group luminosity, consistent with estimates of intracluster light for other groups at a similar mass (e.g. Gonzalez et al., 2007).

With regard to similar types of analyses on other groups and clusters, Coma is the only cluster analysed to a similar depth with stellar population measurements. Smith et al. (2008) have examined radial gradients of Coma cluster dwarf galaxies, finding strong trends towards younger ages and higher metallicities with increasing cluster-centric radii. While these results are at odds with our own, we believe this disagreement to be largely driven by the galaxy selection employed by Smith et al. (2008). The trends observed by Smith et al. (2008) are consistent with the interpretation that the south-west “infall” region of Coma has already undergone a passage through the cluster centre. Observations of younger ages and higher metallicities in a “quenched” dwarf population would then be consistent with the idea of induced star formation from galaxy encounters with the dense/hot IGM (e.g. Poggianti et al., 2004). The fact that we do not see such a trend would seem to suggest that we either fail to measure galaxies at sufficiently large radii to see effects
5.6. Discussion and conclusions

of induced star formation in our galaxies, or that such dramatic interactions are not occurring within the central regions we probe here. Unfortunately our spectroscopic data do not encompass the dynamical substructure identified in Section 3.3.2, and so we are unable to comment on possible stellar population trends at these large radii.

While we do not see any obvious trends of stellar populations with radius, as Smith et al. do, we do perhaps find a more subtle interpretation of galaxy evolution in the group environment through analysis of emission-line properties. Comparison of emission- and absorption-line metallicities has allowed us to extract information regarding the previous star-formation episodes of galaxies through the relation of nebular and stellar metallicities. What we find is that the relative offset between these two metallicity estimates is too large to be explained by either pure passive evolution of galaxies, which can account for at most $\sim 1$ dex of offset, or ongoing star formation, which is inconsistent with other observed galaxy properties. The mass-dependence of our emission–absorption metallicity offset instead is consistent with a scenario in which galaxies are being stripped of their gas primarily through galaxy–IGM interactions, and therefore subsequent ISM enrichment is having a larger effect on the observed emission-line metallicity.
Conclusions

Since previous Chapters each contain a discussion of conclusions on their respective topics, here we simply summarise the primary findings presented throughout this thesis. We then discuss how these conclusions relate to our original goal of tracing group evolution through the use of detailed galaxy studies and future directions for this work.

6.1 Summary

We have used a combination of new spectroscopic observations and literature data in the region of NGC 5044 to assemble the largest-ever velocity-confirmed sample for a single group, and more than a three-fold increase over previous membership for the NGC 5044 group.

- The radial distribution of late- and early-type galaxies is consistent with the presence of a morphology–density relation in that late-type galaxies are found predominantly in outer group regions. When separated by either $B$-band magnitude or stellar mass, subsamples of galaxies show no strong evidence for either spatial or kinematic segregation. Analysis of the Dressler-Shectman $\Delta$ statistic shows some evidence for a small dynamical substructure at $\sim 1.4$ Mpc in projection from the group centre. The large peculiar velocity of NGC 5044 itself relative to the group mean ($\sim 200$ km s$^{-1}$), possible presence of substructure on the outer regions of the group and detection of a “sloshing” type cold front in the group’s X-ray distribution (Gastaldello et al., 2009) suggest that
the group is still growing and in the processes of relaxation, but the group's Gaussian line-of-sight velocity distribution and relatively uniform X-ray profiles argue against any recent, dynamically violent evolution of the group.

- As a test of SSP models and the robustness of their predictions we have used a multi-index $\chi^2$-minimisation technique to fit high signal-to-noise observations of Galactic GCs with a variety SSP model sets. This comparison has shown that, of the parameters we are able to determine from integrated spectra, metallicities are the most robust, showing little to no variation despite comparison to models using a mix of metallicity definitions and $\alpha$-element enhancement schemes. Age and $\alpha$-element abundance measurements are increasingly more difficult to measure; ages in particular exhibit significant scatter in their measurements. The accuracy to which $\alpha$-element abundances can be estimated depends largely on the metallicity of the stellar population being observed and, not surprisingly, the method used to adjust SSP models for varying abundance ratios. For the metallicity dependent enhancement calculations of Korn et al. (2005), the sensitivity of low-metallicity stellar populations to abundance variation is minimal, making the distinction between small variations in $\alpha$-element abundance difficult leading to an apparently spurious trend of ever-increasing element abundance as metallicity decreases. Such a trend is not observed when SSP models are adjusted using a different, non-metallicity-dependent enhancement scheme (Houdashelt et al., 2002), and consequently $\alpha$-element abundances fall more in line with the observed abundances from resolved spectral studies. Concerning application to higher-metallicity galaxy data, however, the differences between models and abundance ratio calculations are minimal.

- In the context of the NGC 5044 group, stellar population parameters show a clear distribution with respect to stellar mass. The mass-metallicity relation observed for our sample galaxies is consistent with that observed in both more- and less-massive environments (as gauged using samples of galaxies from the Local Group and the Shapley supercluster). This suggests that, while the mean mass and metallicity change with environment, galaxies follow a similar relation regardless of where they are found, i.e. stellar metallicities appear
to be driven primarily by internal rather than external processes. $\alpha$-element abundance measurements are noisy, particularly at low masses (or, alternatively, metallicities) where models make measurements increasingly difficult. If we restrict analysis of $\alpha$-element abundances to galaxies with stellar mass greater than $\sim 10^{8.5} M_\odot$, then there is some evidence for a trend of $\alpha$-element abundance increasing with mass, consistent with interpretations of the mass–metallicity relation as a star-formation efficiency/timescale indicator. When we consider a more complex interplay between galaxy properties, we find that galaxies lie on a plane described by stellar mass, metallicity and age, which is shown to be particularly relevant for analyses of the age–metallicity relation when mass selection effects may otherwise obscure a trend. Galaxy ages and $\alpha$-element abundances show no clear variations with radius, remaining largely consistent out to $\sim 500$ kpc. Data show a trend of decreasing mean metallicity with increasing groupcentric radius, however this is shown to be an effect of missing low-metallicity (mass) galaxies from the central group regions. Upon further analysis, galaxies with stellar masses less than $\sim 10^{8.8} M_\odot$ appear absent from the central 100 kpc of the group, supporting photometric observations of a central deficit of dwarf galaxies [Mathews et al., 2004] and consistent with a model in which low-mass galaxies are tidally disrupted through interactions with the group potential.

- The availability of Chandra and XMM observations for the NGC 5044 group has enabled us to undertake a comparison between the galaxy stellar content and abundances measured from the hot IGM. Iron and silicon abundance in the hot gas trace the observed trend of stellar mass-density well where X-ray and galaxy observations overlap, indicative of enrichment from SNIa occurring at late times. While our data support the general interpretation of iron excess as due to outflows from the central galaxy, our data are also consistent with satellite galaxies or intragroup stars contributing significantly towards the build up of metals in the IGM.

- A comparison of nebular (emission-line) and stellar (absorption-line) metallicities shows that the two disagree, with nebular metallicities being up to 1.5 dex higher than their stellar counterparts. The offset between nebular and
stellar metallicities shows a strong dependence on both stellar mass and age dependence such that galaxies with the largest observed offsets are both older and less massive than galaxies with more consistent nebular and stellar metallicities. Considering several scenarios for inducing such an offset, we argue that observed effect is too large to be explained solely through enrichment from evolving stellar populations, instead requiring that gas be removed from galaxies in order to accentuate subsequent enrichment. The combination of mass dependence and lack of a trend with $\alpha$-element abundance leads us to exclude AGN outflows or galaxy–galaxy interactions as dominant mechanisms, instead favouring galaxy-IGM interactions as the dominant removal process.

6.2 NGC 5044 and group evolution

We turn finally to consideration of what the data presented herein can tell us about the evolution of the NGC 5044 group. As discussed in Section (3.4.2) the comparison of dynamics for early- vs. late-type galaxies in the NGC 5044 group shows little evidence for a difference in their velocity distributions. In a scenario where galaxy–IGM interactions dominated the evolution of early-type galaxies — e.g. via gas removal from late-type galaxies — the expectation would be for the early-type galaxy population to have a preferentially broader velocity distribution than late-type galaxies due to the strong dependence of both ram-pressure and Kelvin-Helmholtz Instability on peculiar velocity (see e.g. Eqns. [1.3] and [1.4]). If the early-type population was instead grown predominantly via mergers, which serve to narrow the velocity distribution of merger remnants relative to non-remnant galaxies, then we would expect to observe this lower velocity dispersion in the comparison of late- and early-type galaxy kinematics. The statistically similar kinematic distribution of late- and early-type galaxies suggest that neither galaxy–IGM or galaxy–galaxy interactions have dominated the evolution the NGC 5044 group’s galaxy population, and instead that both have contributed equally to the group’s evolution. Do other data provide further clues to the nature of galaxy evolution in the NGC 5044 group?

We see marginal evidence for an increased population of intermediate-mass star-forming galaxies — relative to lower-mass galaxies — with young central ages,
which could be explained considering the dependence of merger rate on galaxy mass (e.g. Eqn. [1.2]) and the likelihood of star formation in gas-rich mergers. However, as described in Chapter 5, both aperture effects and the errors associated with B-band-based mass estimates can significantly influence our conclusions for these data, and so we are unable to use these galaxies as evidence for a merged population. In addition to the young star-forming galaxy population, we also see some evidence for a 5 – 7 Gyr old passive population of galaxies, which are likely the product of more recently truncated bursts of star formation. While a merging scenario can explain these systems, it is not a unique descriptor of these observations; any process which can either cause a burst of star formation, such as mergers, or truncates already ongoing star formation, such as ram-pressure stripping of in-falling late-type galaxies from the field, can reasonably reproduce an intermediate-age passive population.

These data therefore lend support to a hybrid evolution of galaxies in the NGC 5044 group involving both galaxy–galaxy and galaxy–IGM interactions. As discussed in Chapter 5, we see no evidence of merger-driven star formation in our sample of emission-line galaxies. However, they do show tentative evidence for gas removal via ram-pressure or viscous stripping, which is consistent with the limited measurements available of HI deficiency in several NGC 5044 group galaxies (Sengupta et al., 2007). We propose a scenario where the bulk of the NGC 5044 group’s mass has been built up by several coalesced sub-groups at relatively early times. These ‘preprocessed’ sub-groups provide low-dispersion environments in which early-type galaxies grow predominantly via merging. This scenario provides the means to both efficiently build an early-type galaxy population and smooth out the chemical contributions of SNII, which are flatter in terms of their radial distribution than SNIa (J. Rasmussen 2008, private communication), while remaining consistent with the lack of currently observable young dissipational (e.g. star-forming) merger events. Subsequent evolution of the group has then taken place via infall of smaller sub-groups or single galaxies, which have provided sufficient small-scale dynamical instabilities to form the “sloshing” cold-front observed by Gastaldello et al. (2009) and disturb NGC 5044’s velocity with respect to the group mean velocity, but are small enough to leave no significant, long-lived dynamical substructures. These more recent infalling galaxies are observed as a population of intermediate-age early-type galaxies, most likely formed through the slow exhaustion of their cold-gas reservoir.
6.3 Future directions

Useful constraints on group and group-galaxy evolution will only come through observation of a sample of groups. The present work provides a meaningful motivation for the study of such a sample in detail; similar study of a larger sample of groups is the natural extension of this thesis. It is therefore instructive to consider the conclusions of this work and the future work they motivate.

Independent of environmental effects, there is strong reason to believe that the internal properties of galaxies — i.e. their structure, stellar mass, etc. — play at least some role in shaping their observed properties (e.g. the mass-metallicity relation). However, even in the context of environment, many of the conclusions presented herein regarding kinematic segregation (Chapter 3), tidal destruction of galaxies (Chapter 5) and gas removal/stripping processes (Chapter 5) are highly dependent on galaxy stellar mass. A major downfall of our spectroscopic sample is its selection, which is based on $B$-band magnitudes and therefore strongly influenced by recent star formation and dust. This introduces a potentially significant bias as, at any given stellar mass, we preferentially include galaxies that are either younger or relatively dust free. More recently, deep infrared surveys such as the UKIRT Infrared Deep Sky Survey (UKIDSS) provide a means of constructing mass-limited group catalogues through selections based on infrared magnitudes (i.e. $J$-, $H$- and $K$-band), eliminating many of the problems associated with incomplete sampling in the data presented here.

In addition to how galaxies in the group are sampled, it is useful to consider which groups provide the best targets for follow-up surveys. With respect to the data in this thesis, the NGC 5044 group’s X-ray halo has provided several useful independent constraints on the group’s mass, dynamical state and, perhaps most interestingly, the relationship between galaxy chemical properties and those of the IGM. The results in Chapter 5 suggest that a non-negligible fraction of the observed hot IGM may originate outside the central galaxy at relatively early times in the group’s history, either as ejecta from satellite galaxies or from a significant population of intragroup stars. In addition, the rising abundance of silicon observed in NGC 5044 is a feature apparently common to many groups, indicative of a poorly-mixed (i.e. late) reservoir of $\alpha$-elements. For obvious reasons the data presented in this thesis
are unable to constrain potential sources of $\alpha$-elements in the IGM, however the combination of galaxy and IGM abundance measurements provide a probe of the IGM enrichment history and galaxy star-formation history (SFH) which strongly motivate further detailed study of X-ray bright groups.

One of the most intriguing results presented in this thesis concerns the relationship of absorption- and emission-line metallicities, or rather the contrast between the two as presented in Chapter 5. As discussed, nebular and stellar metallicities trace the distribution of metals in different portions of the galaxy, however are intimately linked by star formation and evolution. By exploiting this connection, the comparison of absorption- and emission-line metallicities can place strong constraints on SFH, uniquely separating galaxies with bursty star-formation from those that have evolved by comparatively passive means. This is particularly relevant in discerning the physical significance of the mass–metallicity relation however, as shown in Chapter 5, it also has the potential to identify galaxies which have lost gas due to environmental effects. The strong constraints offered by such a comparison provide impetus for follow-up research using the large, well characterised star-forming galaxy sample of SDSS and future wide-field spectroscopic surveys.

Despite recent improvements in stellar population models and fitting techniques, there are still significant gains to be made on both fronts. A primary limitation of the original (current) Lick/IDS system is the resolution at which it is defined, $\sim 8$ – $11\,\text{Å}$ (FWHM) depending on wavelength. Recently, several studies have begun examining the effects of this low resolution by applying standard Lick index definitions to higher resolution data obtained with modern spectrographs. In general these studies have show that, with higher resolution data, it is possible to modify central and side-band definitions in such a way as to avoid much of the line contamination present in low-resolution spectra, in some cases halving effects of the age–metallicity degeneracy on single lines (e.g., the EW change of an age-sensitive line for a given change in metallicity; see, e.g., Rogers et al. 2010). Certainly, with respect to the interpretation of GC ages and metallicities, improved line measurements that would allow for increased sensitivity to small age fluctuations would be invaluable in the interpretation of extragalactic GC systems. This holds equally true for the interpretation of galaxy stellar populations, however there we are currently met by both method and modelling difficulties. Therefore, in addition to neces-
nary improvements in the Lick/IDS system, our ability to model composite stellar populations must similarly improve.

Whereas GCs are thought to represent relatively simple stellar systems, the multi-epoch formation scenario favoured for galaxies presents significant problems for stellar population analyses. At GC scales we have shown that SSPs work reasonably well in recovering stellar populations at high metallicities, however in low-metallicity GCs our incomplete knowledge of stellar evolution, in particular the evolution of horizontal branch stars, means that data are generally poorly described. Furthermore, the current limited range of ages and $\alpha$-element abundances probed by available integrated spectra needs to be expanded. The inclusion of Galactic GCs covering a broader range in ages (e.g. Terzan 7 or Pal 12 with intermediate ages) and $\alpha$-element abundances (e.g. Rup 106 or Pal 12 with sub-solar $\alpha$-element abundances) would prove vital to refining the predictions of stellar population models.

The issue of complex stellar populations in galaxies is an important one; in this thesis we have skirted the issue of complexity by applying SSPs to our galaxy data and limiting our analysis to *luminosity-weighted* stellar population properties, however this is a decidedly imperfect approach. There is some scope for improvement in this regard, driven by observations of significant scatter in predictions from separate age-sensitive indices (primarily between $D_n4000$ and the Balmer lines H$\delta$, H$\gamma$ and H$\beta$), and several studies have begun fitting increasingly *complex* exponential and multi-epoch star-formation models to index data ([Ferreras et al., 2004; Serra and Trager, 2007; Rogers et al., 2010]) with varying results. Ultimately, it will be a combination of improvements in index measurement techniques *and* modelling which lead to improvements in analyses of integrated spectra. Such improvements will prove vital to analyses of both GCs and galaxies as the most powerful constraints on formation times and timescales, namely stellar ages and $\alpha$-element abundances, stand the most to gain from improved stellar population estimates.
Bibliography


Baum, W. A.: 1959, PASP 71, 106


Bibliography


Desai, V., Dalcanton, J. J., Aragón-Salamanca, A., Jablonka, P., Poggianti, B.,
Gogarten, S. M., Simard, L., Milvang-Jensen, B., Rudnick, G., Zaritsky, D.,


Dressler, A., Lynden-Bell, D., Burstein, D., Davies, R. L., Faber, S. M., Terlevich,

Dressler, A., Oemler, Jr., A., Couch, W. J., Smail, I., Ellis, R. S., Barger, A.,


Eke, V. R., Baugh, C. M., Cole, S., Frenk, C. S., Norberg, P., Peacock, J. A.,
Baldry, I. K., Bland-Hawthorn, J., Bridges, T., Cannon, R., Colless, M., Collins,
C., Couch, W., Dalton, G., de Propris, R., Driver, S. P., Efstathiou, G., Ellis,
R. S., Glazebrook, K., Jackson, C., Lahav, O., Lewis, I., Lumsden, S., Maddox,


Ferguson, H. C. and Sandage, A.: 1990, *AJ* 100, 1


Maiolino, R., Nagao, T., Grazian, A., Cocchia, F., Marconi, A., Mannucci, F.,
Cimatti, A., Pipino, A., Ballero, S., Calura, F., Chiappini, C., Fontana, A.,


McIntosh, D. H., Guo, Y., Hertzberg, J., Katz, N., Mo, H. J., van den Bosch, F. C.,

McKay, N. P. F., Mundell, C. G., Brough, S., Forbes, D. A., Barnes, D. G., James,


Thomas, D., Maraston, C., and Bender, R.: 2003, *MNRAS* 339, 897


Tripicco, M. J. and Bell, R. A.: 1995, *AJ* 110, 3035


Here we show the results of calibrating the S05 data to the P02 data. Table A.1 shows the adopted error we have associated with these calibrations. Figures A.1, A.2 and A.3 show index-index comparisons for the 11 GCs common between P02 and S05 for each of the three different calibrations.
Table A.1: Summary of errors associated with the calibration of our GC data. Adopted Lick/IDS calibration errors for S05 measured and calibrated using [Worthey (1994)] and [Trager et al. (1998)] index definitions are shown in Columns 2 and 3 respectively.

<table>
<thead>
<tr>
<th>Lick Index</th>
<th>W94 Data</th>
<th>T98 Data</th>
<th>T98 w/o Lick</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hα (Å)</td>
<td>0.665</td>
<td>0.665</td>
<td>0.553</td>
</tr>
<tr>
<td>Hγ (Å)</td>
<td>0.252</td>
<td>0.252</td>
<td>0.156</td>
</tr>
<tr>
<td>CN1 (mag)</td>
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<td>0.023</td>
<td>0.009</td>
</tr>
<tr>
<td>CN2 (mag)</td>
<td>0.031</td>
<td>0.024</td>
<td>0.009</td>
</tr>
<tr>
<td>Ca4227 (Å)</td>
<td>0.166</td>
<td>0.184</td>
<td>0.089</td>
</tr>
<tr>
<td>G4300 (Å)</td>
<td>0.537</td>
<td>0.339</td>
<td>0.155</td>
</tr>
<tr>
<td>HγA (Å)</td>
<td>0.579</td>
<td>0.579</td>
<td>0.222</td>
</tr>
<tr>
<td>HγF (Å)</td>
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<td>0.200</td>
<td>0.052</td>
</tr>
<tr>
<td>Fe4383 (Å)</td>
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<td>0.303</td>
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<tr>
<td>Ca4455 (Å)</td>
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<tr>
<td>Fe4531 (Å)</td>
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<td>C4668 (Å)</td>
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<td>0.305</td>
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<tr>
<td>Hδ (Å)</td>
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<td>0.133</td>
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<tr>
<td>Fe5015 (Å)</td>
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<td>1.258</td>
<td>0.128</td>
</tr>
<tr>
<td>Mg1 (mag)</td>
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<td>0.007</td>
<td>0.006</td>
</tr>
<tr>
<td>Mg2 (mag)</td>
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<td>Fe5270 (Å)</td>
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<td>Fe5335 (Å)</td>
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<td>Fe5709 (Å)</td>
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<td>TiO2 (mag)</td>
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Figure A.1: A comparison of the common GCs between S05 and P02 using the Worthey (1994) index definitions for measurement and calibration. Solid lines are a one-to-one correlation, with dashed lines representing our adopted Lick/IDS conversion error as shown in Column 2 of Table A.1. Indices not included in fits to the SSP models (see Sect. A.1) are shown in grey.
Figure A.2: Identical to Fig. A.1, but with indices measured and calibrated using the Trager et al. (1998) index definitions. Solid lines are a one-to-one correlation, with dashed lines representing our adopted Lick/IDS conversion error as shown in Column 3 of Table A.1.
Figure A.3: Identical to Fig. A.1 but with indices measured using the Trager et al. (1998) index definitions, but without any additional Lick calibration applied. Solid lines are a one-to-one correlation, with dashed lines representing our adopted Lick/IDS conversion error as shown in Column 4 of Table A.1.
As discussed in Section 4.3.2, P02 provide data measured and calibrated using both the W94 and T98 index definitions, however in the text we use only the W94 calibrated data. Here we reproduce Figs. 4.5–4.9 using the P02 and S05 data measured and calibrated using T98 index definitions.
Appendix B. Data calibrated using Trager et al. (1998) index definitions

Figure B.1: [Fe/H] from Harris (1996) plotted against SSP derived metallicities. Symbols represent P02 (squares) and S05 (circles). Numbers in the upper left corner represent the mean offset from the one-to-one line (dashed) and the $\sigma_{rms}$ scatter about that offset, error bars signify a 1$\sigma$ deviation on our SSP fits and $\pm$ 0.1 dex for the Harris [Fe/H] values.
Figure B.2: Zinn & West (1984) scale ages from De Angeli et al. (2005) plotted against SSP derived ages, the dotted line in this case represents the oldest age in each model set. Symbols are the same as in Fig. B.1. Numbers in the upper left corner represent the mean offset from the one-to-one line (dashed) and the $\sigma_{rms}$ scatter about that offset, error bars signify a 1$\sigma$ deviation on our SSP fits.
Figure B.3: SSP derived values of [E/Fe] plotted against high resolution element abundances from Pritzl et al. (2005). Models and symbols are the same as in Figure B.1. Error bars signify a 1σ deviation on our SSP fits and ± 0.1 dex for the high-resolution [α/Fe] values.
Figure B.4: Comparison of fitting results for TMK04, LW05 and V07 based models. Symbols are the same as in previous figures. The dashed line shows the assumed local abundance pattern in stars. GCs fit at the minimum SSP metallicities are not shown.

Figure B.5: [Fe/H] vs. age as derived from our SSP fitting. Symbols and models are the same as in previous figures. The dotted line represents the maximum age for a particular SSP.
Here we show the index errors as a function of signal-to-noise for Lick indices measured on AAOmega spectroscopy. We also show in each figure, for comparison, the index error curves used by Proctor et al. (2008) in their analysis of the 6dFGS.
Figure C.1: Index Error as a function of signal to noise. Solid (black) and dashed (red) lines represent the best fit hyperbolic functions for these data and the 6dFGS DR1 data of P+08 respectively. The vertical dotted line represents our adopted S/N cut of 12.
Figure C.2: Same as Fig. C.1.
Figure C.3: Same as Fig. [C.1]
Figure C.4: Same as Fig. C.1. Fe5406 and Fe5709 indices were not measured in the 6dFGS DR1, so their error curves are omitted.
The following publications contain material that appears in this thesis:

