The Assembly and Chemical Evolution of Nearby Early-type Galaxies

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Faculty of Information and Communication Technology
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“The beginning of wisdom is this: Get wisdom. Though it cost all you have, get understanding.”

*Proverbs 4:7 (NIV)*
Despite the great successes of the current cosmological paradigm at explaining structure formation, especially on large scales, the details of the formation and evolution of structures such as galaxies is ill understood. In this Thesis, we address this important question of galaxy formation by probing the assembly and chemical evolution of nearby galaxies and their globular cluster systems.

To this end, we obtain 144 near-infrared spectra of globular clusters around the giant elliptical galaxy NGC 1407 using DEIMOS. We develop a technique to obtain metallicities of extragalactic globular clusters from near-infrared integrated light spectra. We use the metallicity sensitive calcium ii triplet features around 8600 Å. These spectroscopic metallicities are then compared with those inferred from the integrated colours. Several discrepancies are found and we explore their possible origins and implications.

We use a recently developed method to extract spatially resolved galaxy stellar light spectra from our DEIMOS observations for the three intermediate mass to massive early-type galaxies NGC 1407, NGC 2768 and NGC 4494. We use the calcium triplet to derive galaxy stellar light metallicities and obtain metallicity gradients out to unprecedentedly large galactocentric radii for galaxies of these masses. The derived metallicity gradient of NGC 1407 suggests that it is consistent with having formed from significant amounts of early dissipation, with little subsequent star-formation and major mergers. On the other hand, the metallicity gradient measured in NGC 2768 is consistent with a formation in a dissipational major merger event.

The case of NGC 4494 is then explored in greater detail. While we are unable to measure a significant metallicity gradient for this galaxy, we explore its stellar kinematic and the metallicities and kinematics of its globular cluster system. We also use wide field imaging of the galaxy and globular clusters to inform our conclusions. We then combine these several observational lines of evidence and compare them to predictions from galaxy formation scenarios. In this manner, we are able to conclude that this galaxy is also consistent with a formation in a major merger.

This Thesis shows the power of combined photometric and spectroscopic studies in constraining the formation and evolution of individual galaxies.
Acknowledgements

This Thesis would not have been possible without the help and care of many individuals. First, I am heartily thankful to my parents for their unconditional support and never-ending love. I also thank my skeptical brother Sylvain, who at a young age, unknowingly taught me the importance of coherent and logical argumentation. Today, he is still one of my biggest heroes.

I owe my deepest gratitude to Lorne Nelson, who was a great mentor and MSc supervisor. His generous sponsorship of a trip to Amsterdam to attend a conference has allowed me to meet Frazer Pearce, whom I acknowledge for later introducing me to Duncan. I would like to show my gratitude to Duncan, my supervisor, for offering me a PhD student position in the first place, introducing me to the world of observational extragalactic astronomy and the opportunity to observe at Keck. I thank him for his open-door policy, his patience and his understanding, especially when our opinions diverge. A special mention definitely goes to Rob, whose example of contagious enthusiasm does and will continue to fuel my scientific career. Many thanks to Aaron for his intellectual rigour, patience and thorough review of my work.

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Special mentions also go to other collaborators Jean, Lee and Jay; present and past co-supervisors George and Terry; as well as fellow PhD students Christina, Max, Trevor, Chris and Vince; whose friendship, input and useful comments have greatly enhanced my experience in Melbourne and the quality of my research.

A massive ‘thank you’ to my husband and best friend, Frederick, for his unswerving calm that has been an anchor throughout my PhD adventures. His ability to see the bright side in everything and everyone has seen me through the most difficult seasons of this three and half years quest for knowledge.

In closing, I thank God for the exciting opportunity to contribute to the understanding of the amazingly ordered but complex nature of the Universe.
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 except for 1) Section 4.2.1 which is mainly the work of collaborators Lee Spitler and Vincenzo Pota, 2) theoretical models, which were provided by Philip Hopkins and Kenji Bekki in Chapters 3 and 4, respectively and 3) the analysis presented in Fig. 4.15 which was performed by collaborator Aaron Romanowsky.

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

Caroline Foster
Santiago, Chile
August 2011
Contents

Abstract iii

Contents ix

List of Figures xiii

List of Tables xv

1 Introduction 1

1.1 Classical galaxy formation scenarios . . . . . . . . . . . . . . . . . . . 2
1.2 Early-type galaxies . . . . . . . . . . . . . . . . . . . . . . . . . . . 5
1.3 Globular clusters . . . . . . . . . . . . . . . . . . . . . . . . . . . . 7
1.4 Our approach . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 10
1.5 Thesis structure . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 13

2 Deriving Metallicities From the Integrated Spectra of Extragalactic
Globular Clusters Using the Near-Infrared Calcium Triplet 15

2.1 Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 15
2.2 Data . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 17
2.2.1 Photometry . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 17
2.2.2 Spectroscopy . . . . . . . . . . . . . . . . . . . . . . . . . . . . 21
2.3 Analysis . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 25
2.3.1 Revisiting Armandroff & Zinn (1988) . . . . . . . . . . . . . . 25
2.3.2 Choice of index definition . . . . . . . . . . . . . . . . . . . . . 27
2.3.3 Single stellar population models . . . . . . . . . . . . . . . . . . 30
2.4 Results: The GC system of NGC 1407 . . . . . . . . . . . . . . . . . 32
2.5 Discussion . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 37
2.6 Summary . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 42

3 Metallicities at Large Galactocentric Radii Using the Near-
infrared Calcium Triplet 43

3.1 Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 43
3.2 Sample . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 44
### Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2.1 NGC 1407</td>
<td>44</td>
</tr>
<tr>
<td>3.2.2 NGC 2768</td>
<td>46</td>
</tr>
<tr>
<td>3.2.3 NGC 4494</td>
<td>46</td>
</tr>
<tr>
<td>3.3 Data</td>
<td>47</td>
</tr>
<tr>
<td>3.3.1 Acquisition</td>
<td>47</td>
</tr>
<tr>
<td>3.3.2 Reduction</td>
<td>48</td>
</tr>
<tr>
<td>3.4 Analysis</td>
<td>49</td>
</tr>
<tr>
<td>3.4.1 Index Measurements</td>
<td>49</td>
</tr>
<tr>
<td>3.4.2 Conversion into metallicities</td>
<td>55</td>
</tr>
<tr>
<td>3.5 Results</td>
<td>56</td>
</tr>
<tr>
<td>3.5.1 NGC 1407</td>
<td>58</td>
</tr>
<tr>
<td>3.5.2 NGC 2768</td>
<td>59</td>
</tr>
<tr>
<td>3.5.3 NGC 4494</td>
<td>59</td>
</tr>
<tr>
<td>3.6 Discussion</td>
<td>62</td>
</tr>
<tr>
<td>3.7 Summary</td>
<td>65</td>
</tr>
</tbody>
</table>

### 4 Global Properties of ‘Ordinary’ Early-type Galaxies: photometry and spectroscopy of stars and globular clusters in NGC 4494

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 Introduction</td>
<td>67</td>
</tr>
<tr>
<td>4.2 Data</td>
<td>71</td>
</tr>
<tr>
<td>4.2.1 Imaging acquisition and reduction</td>
<td>71</td>
</tr>
<tr>
<td>4.2.2 Spectroscopy acquisition and reduction</td>
<td>72</td>
</tr>
<tr>
<td>4.3 Analysis and results</td>
<td>73</td>
</tr>
<tr>
<td>4.3.1 Galaxy light</td>
<td>75</td>
</tr>
<tr>
<td>4.3.2 Globular cluster system</td>
<td>86</td>
</tr>
<tr>
<td>4.4 Discussion</td>
<td>100</td>
</tr>
<tr>
<td>4.4.1 Inferences from the stellar light</td>
<td>100</td>
</tr>
<tr>
<td>4.4.2 Inferences from the GC system</td>
<td>103</td>
</tr>
<tr>
<td>4.5 Summary and conclusions</td>
<td>107</td>
</tr>
</tbody>
</table>

### 5 Conclusions

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Summary</td>
<td>111</td>
</tr>
<tr>
<td>5.2 Future work</td>
<td>115</td>
</tr>
<tr>
<td>Contents</td>
<td></td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>---</td>
</tr>
<tr>
<td><strong>Bibliography</strong></td>
<td>119</td>
</tr>
<tr>
<td><strong>A  GC metallicity uncertainty determination</strong></td>
<td>137</td>
</tr>
<tr>
<td><strong>B  Other weak spectral features</strong></td>
<td>141</td>
</tr>
<tr>
<td><strong>Publications</strong></td>
<td>144</td>
</tr>
</tbody>
</table>
List of Figures

1.1 Hubble diagram .......................................................... 2
1.2 Partial copy of figure 12 from [Hoffman et al. 2010] .................. 6

2.1 Colour magnitude diagram for GCs around NGC 1407 ............... 18
2.2 Empirical colour conversion from $(g - i)_0$ to $(B - I)_0$ ............ 19
2.3 Colour histogram of GCs around NGC 1407 .......................... 20
2.4 GC recession velocity histogram for NGC 1407 ....................... 22
2.5 Effects of skyline residuals on CaT as a function of recession velocity 23
2.6 Example GC spectra for NGC 1407 .................................. 24
2.7 An updated reproduction of figure 5 from [AZ88] ..................... 26
2.8 Example fitted GC spectrum ......................................... 28
2.9 Assessment of index measurement systematics ....................... 29
2.10 Relevant predictions from [V03 and BC03 SSP models] ............... 31
2.11 Relationship between metallicity and colour for a sample of NGC 1407 GCs based on [C07] ............................................. 33
2.12 The distribution of NGC 1407 GCs in the $(B - I)_0$-CaT$_{F10}$ plane ......................................................... 34
2.13 Inferred metallicity distribution for our sample of NGC 1407 GCs 36
2.14 Averaged and continuum normalised raw spectra of the brightest blue and red GCs in NGC 1407 ............................................. 36
2.15 Histogram of CaT and inferred metallicity for GCs around NGC 1407 .......................................................... 37

3.1 DSS images of NGC 1407, NGC 2768 and NGC 4494 .................. 44
3.2 Example background spectrum for NGC 2768 ........................ 50
3.3 Example galaxy light spectra for NGC 2768 ........................... 51
3.4 Visual representation of the CaT definition used in Chapter 3 ........ 54
3.5 Applied velocity dispersion index correction .......................... 54
3.6 Predicted relationship between CaT and metallicity for galaxy spectra using the [V03 models] ............................................ 56
3.7 CaT and metallicity gradients in NGC 1407 ............................ 58
3.8 CaT and metallicity gradients in NGC 2768 ............................ 60
3.9 CaT and metallicity gradients in NGC 4494 ............................ 61
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>DSS image of NGC 4494 showing the positions of our science spectra</td>
<td>70</td>
</tr>
<tr>
<td>4.2</td>
<td>Example NGC 4494 GC spectra and fitted templates</td>
<td>73</td>
</tr>
<tr>
<td>4.3</td>
<td>Example NGC 4494 galaxy light spectra and fitted templates</td>
<td>74</td>
</tr>
<tr>
<td>4.4</td>
<td>Surface brightness profiles for NGC 4494</td>
<td>76</td>
</tr>
<tr>
<td>4.5</td>
<td>Variation in CaT and velocity moments of the galaxy light as a function of PA</td>
<td>77</td>
</tr>
<tr>
<td>4.6</td>
<td>Galaxy light and GC kinematic results as a function of radius</td>
<td>80</td>
</tr>
<tr>
<td>4.7</td>
<td>Relationship between $h_3$ and $(V_{\text{obs}} - V_{\text{sys}})/\sigma$</td>
<td>84</td>
</tr>
<tr>
<td>4.8</td>
<td>CaT and colour gradients in NGC 4494</td>
<td>86</td>
</tr>
<tr>
<td>4.9</td>
<td>Colour-colour GC candidate selection for NGC 4494</td>
<td>87</td>
</tr>
<tr>
<td>4.10</td>
<td>CMD of NGC 4494 GCs</td>
<td>90</td>
</tr>
<tr>
<td>4.11</td>
<td>GC surface density profile for NGC 4494</td>
<td>91</td>
</tr>
<tr>
<td>4.12</td>
<td>GC velocity distribution as a function of PA and radius</td>
<td>94</td>
</tr>
<tr>
<td>4.13</td>
<td>NGC 4494 GC kinematics dependence on colour</td>
<td>96</td>
</tr>
<tr>
<td>4.14</td>
<td>CaT and metallicity as a function of colour</td>
<td>98</td>
</tr>
<tr>
<td>4.15</td>
<td>Rotation versus ellipticity diagnostic diagram</td>
<td>102</td>
</tr>
<tr>
<td>4.16</td>
<td>Dependence of GC kinematics on host galaxy properties</td>
<td>106</td>
</tr>
<tr>
<td>A.1</td>
<td>Dependence of CaT and metallicity uncertainties on signal-to-noise</td>
<td>138</td>
</tr>
<tr>
<td>A.2</td>
<td>Variation of the average signal-to-noise as a function of $i$-band apparent magnitude</td>
<td>138</td>
</tr>
<tr>
<td>B.1</td>
<td>Correlation between CaT and other nearby weak spectral features</td>
<td>142</td>
</tr>
<tr>
<td>B.2</td>
<td>Correlation between colour and other weak spectral features</td>
<td>143</td>
</tr>
</tbody>
</table>
## List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Galaxy sample properties</td>
<td>45</td>
</tr>
<tr>
<td>3.2</td>
<td>Sky scaling index definition</td>
<td>47</td>
</tr>
<tr>
<td>3.3</td>
<td>CaT\textsubscript{F09} index definition</td>
<td>53</td>
</tr>
<tr>
<td>3.4</td>
<td>Relevant properties of H09 dissipative major merger simulations</td>
<td>62</td>
</tr>
<tr>
<td>4.1</td>
<td>Properties of nine massive ETGs with significant GC kinematic samples from the literature</td>
<td>69</td>
</tr>
<tr>
<td>4.2</td>
<td>Results of Sérsic fits to the galaxy surface brightness profile of NGC 4494</td>
<td>75</td>
</tr>
<tr>
<td>4.3</td>
<td>Compilation of salient GC kinematic properties in the literature for selected large ETGs</td>
<td>92</td>
</tr>
</tbody>
</table>
# List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACS</td>
<td>Advanced Camera for Surveys</td>
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<tr>
<td>AGN</td>
<td>Active galactic nuclei</td>
</tr>
<tr>
<td>AZ88</td>
<td>Armandroff and Zinn (1988)</td>
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<tr>
<td>B00</td>
<td>Barmby et al. (2000)</td>
</tr>
<tr>
<td>B06</td>
<td>Bergond et al. (2006)</td>
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<tr>
<td>BC03</td>
<td>Bruzual and Charlot (2003)</td>
</tr>
<tr>
<td>BHB</td>
<td>Blue horizontal branch</td>
</tr>
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<td>BS</td>
<td>Blue straggler</td>
</tr>
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<td>C01</td>
<td>Cenarro et al. (2001)</td>
</tr>
<tr>
<td>C03</td>
<td>Côté et al. (2003)</td>
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<tr>
<td>C07</td>
<td>Cenarro et al. (2007)</td>
</tr>
<tr>
<td>CaT</td>
<td>Calcium II Triplet</td>
</tr>
<tr>
<td>CMD</td>
<td>Colour magnitude diagram</td>
</tr>
<tr>
<td>Co01</td>
<td>Côté et al. (2001)</td>
</tr>
<tr>
<td>DEIMOS</td>
<td>DEep Imaging Multi-object Spectrograph</td>
</tr>
<tr>
<td>DGTO</td>
<td>Dwarf-globular transition object</td>
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<tr>
<td>DSS</td>
<td>Digitized Sky Survey</td>
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<tr>
<td>DTT89</td>
<td>Diaz et al. (1989)</td>
</tr>
<tr>
<td>E</td>
<td>Elliptical</td>
</tr>
<tr>
<td>ETG</td>
<td>Early-type galaxy</td>
</tr>
<tr>
<td>F09</td>
<td>Foster et al. (2009)</td>
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<tr>
<td>F10</td>
<td>Foster et al. (2010)</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full width half maximum</td>
</tr>
<tr>
<td>GC</td>
<td>Globular cluster</td>
</tr>
<tr>
<td>H96</td>
<td>Harris (1996)</td>
</tr>
<tr>
<td>H09</td>
<td>Hopkins et al. (2009)</td>
</tr>
<tr>
<td>H08</td>
<td>Hwang et al. (2008)</td>
</tr>
<tr>
<td>HB</td>
<td>Horizontal branch</td>
</tr>
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<td>HST</td>
<td>Hubble Space Telescope</td>
</tr>
<tr>
<td>Acronym</td>
<td>Meaning</td>
</tr>
<tr>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>IMF</td>
<td>Initial mass function</td>
</tr>
<tr>
<td>KDC</td>
<td>Kinematically decoupled core</td>
</tr>
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<td>L10</td>
<td>Lee et al. (2010)</td>
</tr>
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<td>ACDM</td>
<td>Cold Dark Matter with cosmological constant</td>
</tr>
<tr>
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<td>Napolitano et al. (2009)</td>
</tr>
<tr>
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<td>Near-infrared</td>
</tr>
<tr>
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<td>Proctor et al. (2009)</td>
</tr>
<tr>
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<td>Position angle</td>
</tr>
<tr>
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<td>Romanowsky et al. (2009)</td>
</tr>
<tr>
<td>$r_e$</td>
<td>Effective radius</td>
</tr>
<tr>
<td>S</td>
<td>Spiral</td>
</tr>
<tr>
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<td>Lenticular</td>
</tr>
<tr>
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<td>Schuberth et al. (2010)</td>
</tr>
<tr>
<td>SED</td>
<td>Spectral energy distribution</td>
</tr>
<tr>
<td>Sb</td>
<td>Barred spiral</td>
</tr>
<tr>
<td>SDSS</td>
<td>Sloan Digital Sky Survey</td>
</tr>
<tr>
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<td>Stellar Kinematics with Multi-Slits</td>
</tr>
<tr>
<td>SMEAGOL</td>
<td>Spectroscopic Mapping of Early-type Galaxies to their Outer Limits</td>
</tr>
<tr>
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<td>Supernova</td>
</tr>
<tr>
<td>SSP</td>
<td>Single stellar population</td>
</tr>
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<td>UCD</td>
<td>Ultra compact dwarf</td>
</tr>
<tr>
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<td>Vazdekis et al. (2003)</td>
</tr>
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<td>W10a</td>
<td>Woodley et al. (2010a)</td>
</tr>
<tr>
<td>WFPC2</td>
<td>Wide-field Planetary Camera 2</td>
</tr>
</tbody>
</table>
Introduction

In the 1920’s, reliable distance determination to nearby galaxies such as Andromeda (M31, e.g., Opik, 1922; Hubble, 1929) convincingly showed that galaxies are ‘island universes’ (Kant, 1755) independent of our own Milky Way. This settled the famous “Great Debate” that took place between Shapley and Curtis in 1921 (see Hoskin, 1976, for a review), but raised further questions about their origin. Contemporaneously, Hubble (1926) suggested a morphological classification scheme based on close inspection of galaxy images (see Fig. 1.1). Hubble classified galaxies into early-types, which include galaxies of ‘simple’ morphologies such as ellipticals (Es) and lenticulars (S0s); and late-types, which include galaxies of ‘complex’ morphologies such as barred (Sb) and unbarred (S) spirals. This classification as early- and late-type galaxies suggested an “evolutionary sequence” from E-like morphologies into more complex spiral morphologies. No physical processes leading to this sequence was proposed.

Several decades later, we now have a physically motivated theory to (at least partly) explain the origin of structures such as galaxy clusters, galaxies, etc. Indeed, our understanding of cosmology has greatly improved with the development of the General Relativity theory and the successes of the Cold Dark Matter with cosmological constant (ΛCDM) paradigm at describing large-scale structures, the cosmic microwave background, the observed acceleration of the expansion of the Universe, etc. On smaller scales, fundamental questions about the details of the formation and evolution of galaxies are still facing modern astronomy (e.g., Peebles and Nusser, 2010; Kroupa et al., 2010). Despite sustained efforts both on the observational and theoretical fronts, an accepted self-consistent picture of galaxy formation...
Chapter 1. Introduction

Figure 1.1: The Hubble diagram (image credit: Hubble 1936) used to morphologically classify galaxies. Hubble suggested that galaxies evolved from early-types with simple E and S0 morphologies (left-hand side of the diagram) into more complex late-type spiral morphologies (right-hand side of the diagram).

has not yet emerged. Several scenarios have been proposed over the years, the most popular being the early dissipational (or monolithic) collapse and the hierarchical merging scenarios.

1.1 Classical galaxy formation scenarios

The idea of the early dissipative collapse scenario can be traced back to Kant (1755), who suggested that the Galaxy collapsed due to self-gravity. Its popularity increased two centuries later following Eggen et al. (1962), who observed that the motions of the outer, metal-poor, and older halo stars in the Milky Way suggested that the Galaxy collapsed early and rapidly. Under the classical early dissipative collapse paradigm (Larson 1974, 1975; Carlberg 1984; Arimoto and Yoshii 1987), galaxies are thought to form and be assembled early (i.e., at high redshift) via the dissipative collapse of large gas clouds. The gas sinking towards the centre of the potential well fuels the formation of the majority of the stars. This initial star formation period is followed by the quiescent evolution of galaxies with little subsequent star formation and only few possible mergers.

In contrast, Searle and Zinn (1978) found that the radial distribution and spread of abundances of giant stars in Galactic globular clusters (GCs) implied a much more
chaotic formation for the Milky Way. They considered that the best explanation for the spatial distribution of the GC abundances was a formation by merging of smaller fragments as considered by Searle (1977). This provided evidence for the classical hierarchical scenario (Kauffmann et al., 1993; Kauffmann and Charlot, 1998; De Lucia et al., 2006; De Lucia and Blaizot, 2007) under which galaxies form and evolve via the hierarchical merging of sub-units. Star formation is triggered by merger events throughout a galaxy’s history. Under this paradigm, the assembly of galaxies is a continuous process, whereas the scale of the merger induced star formation episodes itself depends on the gas content of the progenitors involved.

Over the years these two scenarios have been refined and modified to accommodate observations and their predictions accordingly updated. The hierarchical merging scenario has gained in popularity over the early dissipative collapse as it is most easily reconcilable with the ΛCDM paradigm. This is despite the fact that some observational constraints such as the correlation of radial metallicity gradients with stellar mass (e.g., Spolaor et al., 2008a,b) or the tightness of observed relations between observable properties of E galaxies such as the fundamental plane (see e.g., Djorgovski and Davis, 1987; Terlevich and Forbes, 2002; Renzini, 2006) may argue for a less chaotic formation scenario such as modern or hybrid versions of the early dissipative collapse scenario (e.g., Schade et al., 1999; Pipino et al., 2008, 2010). In any case, it was recently shown that modern versions of both the early dissipative collapse and hierarchical merging scenarios can successfully produce E-like objects (Kampakoglou et al., 2008), and so the debate still continues.

An important observational constraint to these models was discovered by Cowie et al. (1996), who found that the more massive galaxies formed their stars at higher redshift (i.e., earlier), an effect known as down-sizing and sometimes described as ‘anti-hierarchical’. This phenomenon was later confirmed by several other groups (e.g., Terlevich and Forbes, 2002; Kodama et al., 2004; Tanaka et al., 2005; Abraham et al., 2005).

This has led to the need for a fundamental conceptual modification of the hierarchical scenario. Indeed, using semi-analytic models, De Lucia et al. (2006) have shown that down-sizing can be reconciled with the hierarchical scenario if stars in galaxies *form* ‘anti-hierarchically’ while the host galaxies *assemble* hierarchically (but see Pipino and Matteucci, 2008). In other words, the stars that are found
inside the most massive galaxies today may have formed early in sub-clumps even though their assembly into today’s galaxies is ongoing.

While the tension between these scenarios has significantly diminished, this modern version of the hierarchical merging scenario is still in contrast with the early dissipative collapse scenario wherein both the star formation and the assembly of galaxies happen very early. In fact, “this is a key difference between the hierarchical scenario and the traditional early dissipative collapse picture” (De Lucia et al., 2006). Therefore, in order to constrain and delineate between the various galaxy formation scenarios it is necessary to obtain information about both the assembly and the star formation histories of galaxies.

Other key processes involved during galaxy formation and evolution include (but are not limited to) the accretion and/or dissipation of gas (whether early, via monolithic collapse, or merger induced), feedback processes such as stellar winds, supernova (SN) feedback or active galactic nuclei (AGN), reionisation, etc. Observational clues to the importance of these processes are crucial to our understanding of galaxy formation.

For example, the relative importance of gas dissipation and energy feedback from stellar winds, SN and AGN as star formation quenching mechanisms needs to be constrained observationally. Gas dissipation gives rise to central star formation, and hence metal enrichment. On the other hand, if gas is ejected via some feedback mechanism(s), star formation is inhibited, and with it, metal enrichment. Stellar winds and SN feedback eject gas more efficiently at large galactocentric radii (Matteucci, 1994; Martinelli et al., 1998), while AGN are most efficient at ejecting gas from the centre and sometimes out to large radii (Croton et al., 2006; Wang and Kauffmann, 2008). In principle, this can be studied through looking at radial abundance gradients in a galaxy (e.g., Bekki and Shioya, 1999; Kobayashi and Arimoto, 1999; Hopkins et al., 2009). Moreover, radial metallicity gradients can be a robust delineator between the modern early dissipative collapse and hierarchical scenarios as they are predicted to differ at large radii, with major merger remnants having shallower gradients than in galaxies formed monolithically (e.g., Pipino et al., 2008; Hopkins et al., 2009).

Also, the relative roles played by the mass ratio of the progenitors involved in a galaxy merger (i.e., minor- versus major-merger) and other properties of these
1.2 Early-type galaxies

progenitors (e.g., gas-richness, presence of rotation, etc) in producing the properties of the remnant galaxies observed today need to be understood (e.g., López-Sanjuan et al., 2010; Hopkins et al., 2009, 2010). The properties of progenitor galaxies involved in a merger can be probed by looking for distinct kinematic (e.g., Hopkins et al., 2009, 2010) and morphological signatures in the merger remnant galaxy (e.g., López-Sanjuan et al., 2010), especially at large galactocentric radii. Indeed, Hoffman et al. (2010) predict that the less relaxed intermediate and outer parts of a gas-rich (or wet) disk-disk merger remnant may retain the dynamical signature of the cold disk stars and original halo stars, respectively (see Fig. 1.2). The stellar properties within the inner \( \lesssim 1 \) effective radius \( r_e \) are shaped by stars recently formed through gas dissipation. In this model, a transition in the kinematic properties of the remnant is expected for \( 1 \lesssim r_e \lesssim 3 \), beyond which the kinematics resemble those of a dissipationless (or dry) merger. This is because the outer parts should be built up from the progenitor’s pre-existing disk and halo stars in both cases. Moreover, as a complement to looking for these kinematic signatures, dry merging also leaves an imprint on the distribution of the metals in the remnant such that it washes-out or weakens radial metallicity gradients (e.g., White, 1980; Di Matteo et al., 2009; Pipino et al., 2010).

1.2 Early-type galaxies

Since they contain between half and three quarters of the total stellar mass in the local universe (Bell et al., 2003; Baldry et al., 2004), early-type galaxies (ETGs) such as E and S0 galaxies are a key population to study. Moreover, ETGs are typically more luminous/massive and contain less obscuring dust than spiral galaxies. This simplifies the acquisition and study of their properties (i.e., kinematic, photometric and stellar composition). On the other hand, without the knowledge of the precise star formation history of a given galaxy, probing the stellar populations of the unresolved stellar light yields only the luminosity weighted average population. Because younger stars tend to outshine old ones, the inferred stellar population parameters (e.g., age and metallicity) are disproportionately biased towards those of the most recent star formation episode and may not represent the bulk of the stars (Conroy

\(^1\)The effective radius is the galactocentric radius within which half of a galaxy’s light is enclosed.
Figure 1.2: Partial copy of figure 12 from [Hoffman et al. (2010)](https://doi.org/10.1086/671941) showing the predicted kinematics of gas-poor (upper panels) and gas-rich (lower panels) major merger remnants as a function of probed galactocentric radii. The left, centre and right columns show $1_{rc}$ velocity maps, $3_{rc}$ velocity maps with the $1_{rc}$ maps superimposed inside the boxes and $7_{rc}$ velocity maps, with the $1$ and $3_{rc}$ maps inside the boxes. The predicted kinematics of a gas-rich merger remnant show a transition between $1$ and $3_{rc}$. In a gas-rich merger, the inner parts are dominated by the motions of the new dissipatively formed star, whereas the outer parts record the progenitor’s stellar motions.
et al., 2009; Conroy and Gunn, 2010). Luckily, ETGs tend to be dominated by old stellar populations (∼ 5 Gyr and older). Nevertheless, this effect must be kept in mind as a caveat of any stellar population study of unresolved galaxy light.

The determination of stellar population parameters is further complicated by the subtle effects of the age-metallicity degeneracy (Worthey, 1994). Indeed, old metal-poor populations share certain photometric and spectroscopic properties with those of young metal-rich populations. For example, a young and metal-rich single stellar population (SSP) may have an indistinguishable colour to one that is old and metal-poor. The age-metallicity degeneracy affects photometric studies to a higher degree than spectroscopic studies. For this reason, spectroscopically measured stellar population parameters are more reliable. For unresolved stellar populations, even spectroscopic studies are not immune to the age-metallicity degeneracy as many authors have relied on only one or a few lines measured from blue spectra (e.g., Spinrad et al., 1971; Cohen, 1979; Gorgas et al., 1990; Carollo et al., 1993; Davies et al., 1993; Kobayashi and Arimoto, 1993; Ogando et al., 2005; Forbes et al., 2005; Weijmans et al., 2009) to determine stellar population parameters. In order to fully break the age-metallicity degeneracy, some studies use all the information contained in the spectrum via full spectral fitting (e.g., Tremonti et al., 2004; Chilingarian et al., 2007) while others (e.g., Sánchez-Blázquez et al., 2007; Brough et al., 2007; Spolaor et al., 2008b) have used the technique of Proctor and Sansom (2002), which performs a $\chi^2$ minimisation to fit as many spectral indices as possible, thereby yielding more accurate stellar population values.

1.3 Globular clusters

Another key property of ETGs is that they typically present a larger specific frequency (i.e., number per unit luminosity) of GCs than late-type galaxies (e.g., van den Bergh, 1982; Ashman and Zepf, 1992; Peng et al., 2008). GCs are well approximated as SSPs in which the formation of the vast majority of the member stars are coeval. This approximation greatly simplifies the determination of stellar population parameters of GCs. GCs are generally measured to be old, with ages comparable to the age of the Universe (e.g., Brodie et al., 2005; Strader et al., 2005; Puzia et al., 2005; Cenarro et al., 2005; Norris et al., 2008; Proctor et al., 2008) and thus
probe the very earliest star formation episodes of their host galaxy. This known
old age significantly diminishes the difficulties associated with the age-metallicity
degeneracy (Worthey, 1994).

Understanding GC formation is crucial for understanding galaxy formation, es-
pecially the early epochs (West et al., 2004). For example, although there has been
some debate on its origin (e.g., Yoon et al., 2006; Cantiello and Blakeslee, 2007;
Blakeslee et al., 2010), the nearly ubiquitous colour bimodality of the GC systems of
most galaxies (Larsen et al., 2001; Kundu and Whitmore, 2001; Brodie and Strader,
2006) is usually interpreted as a ubiquitous metallicity bimodality with the blue
and red GCs being metal-poor and -rich, respectively. Very few galaxies have had
a sizable fraction of their GCs’ metallicities determined spectroscopically, such that
the question of the ubiquity of the metallicity bimodality is still being questionned
(e.g., Blakeslee et al., 2010; Caldwell et al., 2011). If it proves true, the ubiquity of
the metallicity bimodality of GC systems is a stringent constraint for galaxy forma-
tion scenarios that must provide at least two formation episodes or mechanisms to
explain the bimodality (e.g., Lee et al., 2010; but see Muratov and Gnedin, 2010).

Furthermore, it has been suggested, based on model predictions and the similar-
ities of the respective spatial distribution (e.g., Forbes et al., 2004) and abundances
(e.g., Harris and Harris, 2002; Woodley et al., 2010b), that red GCs are associated
with the galaxy stars, while blue GCs are associated with the X-ray halo of their
host galaxy (also see e.g. Minniti, 1996; Boley et al., 2009). This possible connection
implies that GCs could in principle be used as proxies for probing the properties
of galaxies out to very large galactocentric radii where they have higher surface
brightness than the galaxy light itself.

Several formation scenarios for GCs have been proposed, all of them intimately
linked to the host galaxy’s formation. Because numerical simulations have only re-
cently resolved GC-size objects (Griffen et al., 2010), GC formation theory is still in
its infancy and often based on qualitative arguments. For our purposes, we divide
GC formation scenarios into three main families (see Brodie and Strader, 2006; Lee
et al., 2010, for good reviews), which we will call the multi-phase collapse, hierar-
chical and hybrid scenarios. We emphasise that this division is by no means sharply
defined as some scenarios could easily fit into more than one category, nevertheless
we use this to help contrast GC formation scenarios with the popular galaxy
1.3. Globular clusters

The multi-phase collapse GC formation scenario is based on the early dissipative collapse galaxy formation scenario (e.g., Larson, 1975; Carlberg, 1984; Arimoto and Yoshii, 1987; Pipino et al., 2010). It proposes that the blue, metal-poor GCs are formed during the first collapse of a large gas cloud. Star formation is subsequently halted briefly some time during this initial collapse. One proposed mechanism to halt the star formation is reionisation (also in Moore et al., 2006), but the feasibility of this scenario has never been checked quantitatively and it is not clear how reionisation could yield similar GC metallicity/colour distributions in all environments. Nevertheless, shortly after this short quiescent episode and as the gas cools down again, a second collapse phase occurs forming a population of slightly younger and metal enriched (i.e., red) GCs (see Forbes et al., 1997, for more details).

In the hierarchical GC formation scenarios (e.g., Cote et al., 1998; Beasley et al., 2002; Bekki et al., 2005; Strader et al., 2005; Moore et al., 2006; Muratov and Gnedin, 2010), GCs are formed in the initial collapse of sub-clumps of gas that later merge. The model proposed by Cote et al. (1998) suggests that metal-rich and -poor GCs are formed as the original GCs of larger and smaller proto-galaxies, respectively. Dissipationless minor merging may sometimes give rise to the metallicity bimodality depending on the merger history. The models of Muratov and Gnedin (2010) allow for subsequent metal-rich GC formation in gas-rich mergers. This is similar to the hybrid models, wherein blue GCs are formed from an initial collapse, while metal-rich GCs are formed during gas-rich galaxy mergers (e.g., Ashman et al., 1994; Bekki et al., 2002).

A recent and extensive GC study is that of the kinematics and stellar populations of a statistically sizable fraction of the GC system of the nearby giant ETG NGC 5128 by Woodley et al. (2010a,b). They find that the majority of the GCs in both subpopulations are old with a significant population of young metal-rich GCs forming later. They conclude that these young metal-rich GCs may have been formed in a more recent merging event than the bulk of the GCs. Moreover, both metal-rich and -poor GC subpopulations are found to be pressure supported with only mild rotation for the metal-rich GCs. From this, they are able to infer that the GC system of NGC 5128 is consistent with a hierarchical formation in a scenario similar to that proposed by Beasley et al. (2002) and Strader et al. (2005). In this
scenario, the blue GCs form in an early collapse of small proto-galaxies and are thus expected to be uniformly old as observed. On the other hand, the bulk of the field stars and metal-rich clusters form slightly later during a second collapse following the early hierarchical assembly of the proto-galaxies. The younger metal-rich GCs suggest subsequent major accretion and/or a recent star forming event. This scenario naturally explains the somewhat unorganised motions of both subpopulations. This study demonstrates the power of spectroscopic studies of large samples of GCs to constrain the formation and assembly history of individual galaxies.

1.4 Our approach

As outlined so far, in order to obtain a complete picture and understanding of galaxy formation, and discriminate between the various scenarios, it is necessary to spectroscopically probe both the global kinematics and stellar populations present in galaxies and their GC systems out to large galactocentric radii (i.e., > 1r_e). Such information about a galaxy’s formation and subsequent evolution can be inferred by looking at the spatial distribution, motion and stellar population parameters of its constituent stars as they are observed today. This can be done accurately via studying individual member stars. Unfortunately, except for a handful of very nearby galaxies (including our own), it is not possible to resolve individual stars even with the most powerful telescopes available today. One must therefore find means of extracting information about the star formation and enrichment history from the integrated light of stellar populations.

Moreover, the low surface brightness of galaxies in their outskirts hinders spectroscopic studies at large galactocentric radii. Spatially resolved kinematic and stellar population studies of the stellar light of large ETGs are typically confined to the inner regions (≤ 1r_e, e.g., Reda et al., 2007; Emsellem et al., 2007, 2011; Kuntschner et al., 2010), thereby probing less than half the stellar light and potentially missing important halo properties. To remedy this, Weijmans et al. (2009) have used long integrations with the SAURON instrument to obtain a few data points at galactocentric radii of up to ~ 4r_e in the ETGs NGC 821 and NGC 3379. Alternatively, Proctor et al. (2009, hereafter P09) and Norris et al. (2008) have developed a technique that takes advantage of the large field-of-view of multi-object spectrographs.
to extract galaxy light spectra from background spectra (sky + galaxy light) of GC multi-slit observations and derive spatially resolved kinematics out to $\sim 3r_e$ (P09). In contrast, kinematic and stellar population information for GCs can be extracted out to very large radii ($10r_e$) but are difficult to obtain in the inner regions where the galaxy background light dominates. Therefore, until recently (Forbes et al., 2004), there has been a discrepancy between the radii probed by studies of GCs and galaxy stellar light.

Using the DEep Imaging Multi-object Spectrograph (DEIMOS) on the Keck II telescope (Faber et al., 2003), we obtain sizeable samples of GC spectra around several large E galaxies. The spectra cover wavelengths between $\sim 6500$-$9000$ Å. The most prominent feature in this wavelength range is the near-infrared Calcium II triplet (CaT). The three distinctive features which comprise the CaT allow for accurate measurements of GC recession velocities. Using the technique of P09, one can extract galaxy background light from the same slits as the GC spectra. This guarantees spatial overlap between the GC data and the galaxy stellar light data. Kinematic properties of the galaxy light at large galactocentric radii were obtained in P09 for a small sample of nearby galaxies.

The galaxy kinematic information is helpful in finding signatures of past mergers (e.g., kinematic decoupled cores, outer rotation, etc) and thus yielding clues towards understanding their assembly history. However, as outlined above, in order to properly delineate between the most popular galaxy formation scenarios one must also obtain stellar population parameters. Conveniently, the CaT has been shown by various groups to be a good tracer of overall metallicity (e.g., Armandroff and Zinn 1988, hereafter AZ88; Diaz et al. 1989; Cenarro et al. 2001; Battaglia et al. 2008) with little age sensitivity for ages $\geq 2.5$ Gyr (e.g., Diaz et al. 1989; Schiavon et al. 2000; Vazdekis et al. 2003; Cole et al. 2004; Carrera et al. 2007), thus minimising the effects of the age-metallicity degeneracy.

It has been shown empirically, that the CaT features are most sensitive to the overall metallicity $[Fe/H]$ rather than to the $[Ca/Fe]$-ratio (e.g., Armandroff and Zinn 1988; Cole et al. 2004; Cenarro et al. 2002). This is because near-infrared integrated light spectra of old stellar populations such as most ETGs and GCs are dominated by the light from red giant stars. A metal-rich red giant star has lower surface gravity than a metal-poor one (AZ88). While $[Ca/Fe]$ does have a small
Chapter 1. Introduction

influence (e.g., Cole et al., 2004; Koch et al., 2008), the dominant contributor to the total equivalent width of the CaT spectral lines comes from the pressure-broadened wings, which are primarily sensitive to gravity (i.e., \( \log(g) \); e.g., Jorgensen et al., 1992; Cenarro et al., 2002). To first order, the high sensitivity of the CaT features to gravity explains their sensitivity to the overall metallicity (i.e., \([\text{Fe/H}]\); Battaglia et al., 2008). Therefore, one can in principle use the near-infrared CaT equivalent widths as a metallicity indicator for integrated light spectra of ‘old’ (\( \geq 2.5 \text{ Gyr} \)) stellar populations. This has already been done for both the integrated light of Galactic GCs (Bica and Alloin, 1987; AZ88) and nearby galaxies (e.g., Diaz et al., 1989; Saglia et al., 2002; Michielsen et al., 2003).

On the theoretical front, single stellar population models at infrared wavelengths have only recently been available (e.g., Bruzual and Charlot, 2003, hereafter BC03; Maraston et al., 2003; Vazdekis et al., 2003, hereafter V03) and their predictions are sometimes discrepant, possibly due to the limited metallicity and age ranges covered by their respective input stellar spectral libraries. Thus, while an objective relative comparison of metallicities based on CaT line strengths is possible, the absolute metallicity value itself will depend on which model set is chosen. Nevertheless, empirical calibrations such as that AZ88 based on Galactic GCs reveal a remarkably tight linear relationship between their CaT index values and metallicity in ‘old’ stellar populations.

Therefore, using DEIMOS we obtain kinematics and stellar population information from the innermost regions out to several effective radii by combining the data from GC and galaxy halo light spectra. This information is used to put stringent constraints on galaxy formation models. A distinctive advantage of this technique is that stellar population parameters and kinematics can be obtained for both GCs and galaxy stellar light simultaneously from a single observation for no additional observational cost.

In this Thesis, we focus on the three nearby ETGs: NGC 1407, NGC 2768 and NGC 4494. The data are obtained as part of the SMEAGOL and SLUGGS surveys. In particular, NGC 1407 was selected for its large GC system, NGC 2768 for the high signal-to-noise and quality of the spectroscopic data, and NGC 4494 was chosen as a prototypical or “ordinary” ETG (e.g., Capaccioli et al., 1992; Lackner and Ostriker, 1987).

\(^{2}\)http://sages.ucolick.org/surveys.html
1.5 Thesis structure

This thesis is divided as follows: in this Chapter, we give an overview of the past and current understanding of galaxy formation and evolution. We also outline the importance of spectroscopic studies of both galaxy stellar light and GCs for understanding the chemical evolution and assembly of individual galaxies. We highlight that, to date, studies of the galaxy stellar light have mostly focused on the very inner parts of galaxies (i.e., $r \lesssim r_e$), thereby missing up to half of the stellar mass. On the other hand, only a handful of large galaxies have had a significant fraction of their GC system observed spectroscopically to extract statistically significant properties of their stellar populations and kinematics.

In Chapter 2, we use a sample of 144 integrated light DEIMOS spectra of GCs around the brightest group galaxy NGC 1407 to show that the CaT index can be used as a metallicity indicator for extragalactic GCs. We also show that different sets of single stellar population models make different predictions for the behaviour of the CaT as a function of metallicity. The metallicities of the GCs around NGC 1407 are obtained from CaT index values using an empirical conversion. The measured CaT/metallicity distributions show unexpected features, the implications of which are discussed in detail.

Chapter 3 describes a new spectroscopic technique for measuring radial metallicity gradients out to large galactocentric radii. We use the galaxy spectrum extraction technique of P09. We also make use of the metallicity sensitive near-infrared CaT features together with SSP models to obtain metallicities. Our technique is applied as a pilot study to a sample of three relatively nearby ($\leq 30$ Mpc) intermediate-mass to massive early-type galaxies. Our derived metallicities are compared with literature values for the inner regions and show good agreement. We compare our metallicity gradients at large radii with profiles from dissipational disk-disk major merger simulations. Based on our metallicity gradients and other observational evidence and theoretical predictions, formation scenarios are discussed for each galaxies in our sample. The limitations of our new technique are also discussed.

We bring together the techniques described in P09, Chapter 2 and Chapter 3 to
present a comprehensive analysis of the spatial, kinematic, and chemical properties of stars and GCs in the ‘ordinary’ E galaxy NGC 4494 in Chapter 4. We publish a catalogue of 431 GC candidates brighter than $i_0 = 24$ based on the photometry, of which 109 are confirmed spectroscopically and 54 have measured spectroscopic metallicities. We also report the discovery of 3 spectroscopically confirmed ultra-compact dwarfs around NGC 4494. We compare the observed properties of NGC 4494 to theoretical predictions and major merger simulations.

A summary of the major findings of the previous Chapters and conclusions are presented and discussed in Chapter 5. We advocate that complete studies of individual galaxies incorporating photometry and spectroscopy of stars and GCs, especially at large galactocentric radii, are an invaluable tool for reconstructing the assembly and chemical evolution of galaxies. These put constraints that can then inform galaxy formation models and improve our understanding of the origin of galaxies. Future directions are also discussed.
2

Deriving Metallicities From the Integrated Spectra of Extragalactic Globular Clusters Using the Near-Infrared Calcium Triplet

2.1 Introduction

The study presented in this Chapter concentrates on the giant E galaxy NGC 1407, a brightest group galaxy (BGG) dominating the Eridanus A group (Brough et al., 2006). It harbours a rich GC system whose colour distribution is unquestionably bimodal (Perrett et al., 1997; Harris et al., 2006; Forbes et al., 2006, 2011).

As with other BGGs and brightest cluster galaxies (e.g., Harris, 2009b), the blue GC subpopulation of NGC 1407 shows a trend of colour with luminosity such that brighter GCs have redder colours on average. This ‘blue tilt’ has been observed in several, usually massive, galaxies of different morphological types and is usually interpreted as a mass-metallicity relationship (see Strader et al., 2006; Harris et al., 2006; Mieske et al., 2006; Spitler et al., 2006; Strader and Smith, 2008; Bailin and Harris, 2009; Forbes et al., 2010). This interpretation has been questioned by some (Kundu, 2008; Waters et al., 2009) who argue that the blue tilt is an artifact caused by using fixed aperture photometry on the partially resolved brightest blue GCs on the Hubble Space Telescope (HST) images. However, the reality of the blue tilt has now been convincingly confirmed using appropriate photometric techniques for resolved sources (Harris, 2009a; Peng et al., 2009) and has even been observed using
Chapter 2. Deriving Metallicities From the Integrated Spectra of Extragalactic Globular Clusters Using the Near-Infrared Calcium Triplet

unresolved ground based images (e.g., [Forte et al. 2007]).

In order to assess the formation history, enrichment history, confirm the origin of the colour bimodality and the blue tilt in GC systems, statistically significant samples of spectroscopically determined metallicities of GCs are required. Spectroscopic data of large GC samples are rare and typically time consuming to acquire. However, using the DEIMOS multi-object spectrograph on Keck it is possible to obtain over 100 integrated light spectra of GCs simultaneously. Using DEIMOS, we have obtained a sizeable spectral sample of kinematically confirmed GCs around NGC 1407 suitable for stellar population analysis.

The sensitivity of DEIMOS is good at red wavelengths near the region of the CaT (8498, 8542, and 8662 Å). The CaT is known to correlate with metallicity for integrated light spectroscopy of Galactic GCs (Bica and Alloin 1987; AZ88). The CaT has also been studied as a potential metallicity indicator for integrated light of galaxies in the past with varying degrees of success. The word ‘puzzle’ has been put forward with regards to its ‘unexpected’ behaviour with metallicity. For example, the CaT was found to be lower than predicted by theory in giant E galaxies (Saglia et al., 2002) and higher than predicted in dwarf E galaxies (Michielsen et al., 2003). Possible resolution of the puzzle has been obtained by comparing CaT strengths to metallicities determined using optical spectra in dwarf Es rather than metallicities derived from narrow-band photometry (Michielsen et al., 2007). Nevertheless, Cenarro et al. (2008a) were able to successfully use the CaT to probe the metallicity gradients of M32. Therefore, while the behaviour of the CaT with respect to metallicity has been studied for the integrated light spectra of galaxies, which are composite stellar populations, with varying degrees of success, it is worth investigating whether it can be used straightforwardly as a metallicity indicator for the integrated light of SSPs such as extragalactic GCs.

This Chapter is divided as follows: our data are presented in Section 2.2. In Section 2.3 we analyse the observational and theoretical behaviour of the CaT with metallicity and present our choice of CaT index definition. Results can be found in Section 2.4. Finally, a discussion and our conclusions are given in Sections 2.5 and 2.6, respectively.
2.2 Data

2.2.1 Photometry

The photometric data consist of imaging of the central region (3.4 x 3.4 arcmin) from the Advanced Camera for Surveys (ACS) mounted on the HST with both the F435W (B) and F814W (I) bands. The ACS dataset has been independently analysed and published by both Forbes et al. (2006) and Harris et al. (2006). Here this is supplemented by Subaru/Suprime-Cam images covering a wider field of view (34 x 27 arcmin) in the SDSS g, r, and i filters (see Spitler et al. 2011, in preparation). Globular cluster candidates in the central region imaged by both Suprime-Cam and ACS thus have photometry in the B, I, g, r, and i filters while those outside the ACS field only have g-, r-, and i-band photometry. In all cases, the reddening corrections were performed according to the DIRBE dust maps (Schlegel et al., 1998).

Both Forbes et al. (2006) and Harris et al. (2006) find a relationship between colour and luminosity for the blue GC subpopulation (blue tilt) in their ACS imaging of NGC 1407. Kundu (2008) and Waters et al. (2009) have argued that the blue tilt in M87 (also a massive E galaxy) could be a photometric bias caused by the resolved sizes of the brightest metal-poor GCs in the HST/ACS images as opposed to an intrinsic astrophysical phenomenon. However, these claims have recently been refuted by both Harris (2009b) and Peng et al. (2009).

The Subaru/Suprime-Cam colour magnitude diagram (CMD) for all photometrically selected GC candidates brighter than \( i = 23.0 \) around NGC 1407 is shown in Figure 2.1. This apparent magnitude limit corresponds to an absolute magnitude of \( M_i = -8.9 \) when assuming the average redshift independent distance modulus \( (m - M) = 31.9 \) given in NED.\(^1\) The CMD reveals a bimodal GC distribution, in agreement with Forbes et al. (2006) and Harris et al. (2006). The photometric blue tilt is apparent and there is no equivalent red tilt. We also show our spectroscopic subsample and compute the running average for both the red and blue subpopulations. The distribution of our selected spectroscopic subsample in the CMD is representative of the underlying GC colour distribution for \( i \leq 22.0 \) (or \( M_i \leq -9.9 \)).

\(^1\)NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.
Figure 2.1: Colour magnitude diagram for NGC 1407 GCs brighter than $i = 23.0$ from Subaru/Suprime-Cam data. Grey points show the position of all photometrically selected GC candidates (including a small number of potential NGC 1400 GCs). Red and blue points show the spectroscopically confirmed GCs with CaT measurements. A running average (solid blue and red lines) of our sample has been overplotted for both GC subpopulations indicating a blue tilt but no red tilt. The colour division is $(g - i)_0 = 0.93$ following Romanowsky et al. (2009). The top x-axis shows the colour conversion that we derive in Figure 2.2 for comparison.
2.2. Data

Figure 2.2: Empirical colour conversion from \((g-i)_0\) to \((B-I)_0\). The top panel shows the least squares linear fit to the data. One outlier due to crowding was removed from the fit and is not shown. Differences between converted and actual \((B-I)_0\) colours with galactocentric radius are shown underneath. These residuals decrease with radius down to a few hundredth of a mag for radii \(\gtrsim 1.0\) arcmin.

In order to obtain \((B-I)_0\) colours and combine both datasets (i.e. HST/ACS and Subaru/Suprime-Cam) we have used the candidates in the common central region to derive the following empirical conversion between \((g-i)_0\) and \((B-I)_0\) colours:

\[
(B-I)_0 = (1.40 \pm 0.05)(g-i)_0 + (0.49 \pm 0.04). \tag{2.1}
\]

This conversion is useful for comparing our results to SSP models that do not always provide SDSS colours (see Section 2.3.3). Figure 2.2 shows the colour conversion as well as the residuals with projected galactocentric radius. The residuals are slightly higher at small projected galactocentric radii due to crowding and the more uncertain Subaru photometry near the centre, where NGC 1407’s surface brightness is high. However, as we move to larger projected radii the uncertainty in the converted \((B-I)_0\) is reduced to only a few hundredth of a mag (see the lower panel of Figure 2.2).

In Figure 2.3 we show both the colour histogram of our combined data and the spectroscopic subsample, whose colour distribution is representative of that of the combined data. In order to directly compare with previous literature, we apply the heteroscedastic (unequal widths) KMM test to all candidates within galactocentric
Figure 2.3: Colour histogram of our combined (Subaru/Suprime-Cam and HST/ACS) photometric data for all GC candidates with $i \leq 23.0$ (black) and our spectroscopic subsample scaled by a factor of 10 for clarity (grey). Overlaid are the Gaussian profiles estimated by the KMM test (assuming heteroscedasticity) with mean blue and red peaks at $(B-I)_0 = 1.57$ and 2.00, respectively, for the whole photometric sample.

This yields $(B-I)_0 = 1.62$ and 2.07 for the mean colour of the blue and red GC subpopulations, respectively. These values are in good agreement with the previous comparable analyses based on ACS imaging of Harris et al. (2006) and Forbes et al. (2006) who found blue peaks at 1.63 and 1.61, and red peaks at 2.07 and 2.06, respectively. However, because of radial colour gradients (Forbes et al., 2011), the larger Subaru field of view has peaks at $(B-I)_0 = 1.57$ and 2.00 with widths of 0.15 and 0.16 for the blue and red GC subpopulations around NGC 1407, respectively. Using the SSP models of V03 the difference in the average $(B-I)_0$ colours for the two subpopulations translates into a metallicity difference of $\Delta[Fe/H] \approx 1.0$ for a fixed old age ($\sim 13$ Gyr) or an age difference of $> 8$ Gyr assuming a fixed moderate metallicity of $[Fe/H] = -0.38$ for all GCs. The latter can be ruled out because an age difference as large as 8 Gyr would have already been detected spectroscopically (see C07). We refer the reader to Spitler et al. (2011, in preparation) and Forbes et al. (2011) for further details on the photometry.
2.2. Data

2.2.2 Spectroscopy

Acquisition

The Keck/DEIMOS spectroscopic data of our photometrically selected GC candidates was obtained during two distinct observing runs.

First, three masks were observed on the nights of 2006 November 19-21. The 1200 l mm\(^{-1}\) grating with 7500 Å central wavelength and 1 arcsec slit width was used. Details of the first observing run can be found in Romanowsky et al. (2009, hereafter R09). The second observing run occurred on the nights of the 2007 November 12-14 under good seeing conditions (typically \(\sim 0.7\) arcsec). Three masks were observed with similar instrumental setup as that of R09. The 1200 l mm\(^{-1}\) grating centred on 7800 Å was used. The setup for both observing runs allows coverage of the wavelength range \(\sim 7550 - 8900\) Å at redder wavelengths with a resolution of \(\sim 1.5\) Å (FWHM) around the CaT features. Using this setup, we also occasionally cover H\(_\alpha\) (6563 Å) at bluer wavelengths for a small fraction of our objects. Four 30 minute exposures were taken on each mask, yielding a total exposure time of 2 hours.

Data reduction

The reduction of the 2006 data is described in R09. As with the 2006 data, the idl spec2d data reduction pipeline written for the DEEP2 galaxy survey was used to reduce the 2007 DEIMOS data. Flat-fielding using internal flats, wavelength calibration using ArKrNeXe arc lamps, as well as the local sky subtraction are performed within the pipeline. The spectra were then cross-correlated with the solar spectrum to extract radial velocities using the FXCOR routine in IRAF\(^2\). Using these velocities, it was possible to clearly distinguish between GCs belonging to NGC 1407, background unresolved galaxies and foreground stars. One mask included some NGC 1400 GCs, but those were easily identified because of the significantly different recession velocity of NGC 1400 (558 km s\(^{-1}\), NED) and its GC system from that of NGC 1407 (1779 km s\(^{-1}\), NED) as seen from Figure 2.4 (see also R09). The velocity selection yielded 113 new confirmed GCs around NGC 1407. These data

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\(^2\)IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under the cooperative agreement with the National Science Foundation.
Figure 2.4: Histogram showing the recession velocity of all confirmed GCs around NGC 1400 and NGC 1407. The systemic velocities of NGC 1400 and NGC 1407 are labelled to show that their respective GC systems are easily delineated in velocity space with a gap at $\sim 1000$ km s$^{-1}$.

were supplemented by those of R09 to give a total of 274 distinct confirmed GCs. The radial velocities of the 7 objects in common between both the 2006 and 2007 data show very good agreement with an rms scatter of only 11 km s$^{-1}$.

Because the NIR region of the spectrum is strongly affected by skylines we find that residual skylines in our raw spectra leftover from the sky subtraction influence our index measurements. This is particularly true for recession velocities $\lesssim 500$, $\sim 1500$ and $\sim 3100–3800$ km s$^{-1}$, where part of all three CaT features simultaneously fall in regions affected by skylines (see Fig. 2.5). In order to counteract this, the spectra are template fitted with the pPXF code of Cappellari and Emsellem (2004) using 13 stellar templates that were observed during the 2007 November run with the same instrumental setup as the GC data. The templates include 11 giant and 2 dwarf stars spanning spectral types from F to early M and a wide range in CaT depth. Known problematic regions of the spectrum with strong skylines were excluded during the fitting procedure (see P09 and Chapter 3). The pPXF routine redshifts, broadens, and chooses the weighted combination of the templates that minimises the residuals between the raw spectrum and the fit. The routine is unable to fit the noisiest spectra as well as the incomplete spectra affected by vignetting due to their position near the edges of the DEIMOS mask. These $\sim 20$ spectra are not
Figure 2.5: Shifted, broadened and arbitrarily normalised sky spectra showing the effect of skylines on the CaT and Hα as a function of recession velocity. High profiles indicate regions where skylines overlap with Hα, Ca1, Ca2 and Ca3 for the first, second, third and fourth panel from the top, respectively. The lower panel shows regions where all three CaT features are affected by skylines. Recession velocities of \( \lesssim 500 \), \( \sim 1500 \) and \( \sim 3100 \)–\( 3800 \) km s\(^{-1}\) have skylines overlapping with all three CaT features.

Figure 2.6 shows examples of template fitted spectra for one of the brightest and one of the faintest GCs in our final sample. The residuals are mostly uniform but showing some features that are mostly associated with the position of known skylines, indicating that template mismatch is not significant. Next, the best fit spectra are continuum normalised interactively using the IRAF CONTINUUM routine with a spline3 function of order typically \( \sim 4 \) and a higher and (stricter) lower sigma
clipping to ensure that spectral features are not fitted. This sets the continuum to unity. In what follows, we will refer to these pPXF and continuum normalised spectra as “fitted spectra” in order to distinguish them from the “raw spectra” output from the DEIMOS pipeline. Finally, the fitted spectra with a raw average number of counts less than 80 were removed from the sample. This corresponds to an apparent/absolute $i$-band magnitude and signal-to-noise ratio cut of approximately 22.0/–9.9 mag and 9 per Å, respectively (see Appendix A). The final sample contains 144 GCs associated with NGC 1407.

The index values are measured on both the fitted and raw spectra. Determination of the uncertainties on the index values is discussed in Appendix A.
2.3 Analysis

In this section, we first review the observational evidence for the sensitivity of the CaT to metallicity in the integrated light spectra of GCs. We then describe and motivate our choice of CaT index definition. We apply our index definition to model spectra from V03 and BC03 in order to better understand theoretically the behaviour of the CaT with metallicity. These will form the observational and theoretical bases on which our results are obtained and discussed.

2.3.1 Revisiting Armandroff & Zinn (1988)

The CaT was first recognised as a potential metallicity indicator in the works of Bica and Alloin (1987) and AZ88. In particular, the latter obtained integrated spectra of Galactic GCs to measure a CaT index (CaT$_{AZ88}$) that they then compared to averaged literature metallicity measurements. After removing the data points with uncertain metallicity measurements they used linear regression to fit a straight line to the remaining 7 data points (i.e. 47 Tuc, NGC 362, NGC 1851, NGC 5927, NGC 6093, M15, and M2). They obtained the linear relationship:

$$[Fe/H] = -4.146 + 0.561 \times \text{CaT}_{AZ88},$$

with rms scatter of only 0.12 dex. This relationship is shown in Figure 2.7. The metallicities are the average between the quoted values in the literature at the time and their CaT$_{AZ88}$ derived values.

There exists more recent metallicity measurements for several GCs and it is worthwhile to verify that the then observed tight correlation still holds with these newer data. In Figure 2.7, the new measurements as compiled in the 2003 updated version of the Catalogue of Parameters for Milky Way Globular Clusters (Harris, 1996, hereafter H96) are also shown. In what follows, we use $[Fe/H]$ to denote metallicities although the metallicities given in both AZ88 and H96 (and hence herein) are based on the Zinn and West (1984) metallicity scale, which is not a strict Fe scale (e.g., Carretta and Gratton, 1997; Rutledge et al., 1997b).

Immediately striking in Figure 2.7 are the 4 circled data points. These are 4 of the 8 GCs for which AZ88 were the first to give a metallicity estimate. The
Figure 2.7: An updated reproduction of figure 5 from AZ88 showing the tight correlation between CaT$_{AZ88}$ and [Fe/H]. CaT$_{AZ88}$ index values are taken directly from AZ88. Hollow squares are the metallicity measurements quoted by AZ88. Stars represent updated [Fe/H] values from H96 (2003 update) with filled symbols showing the 7 points chosen by AZ88 to determine their relationship (solid line). Dotted lines are drawn between the corresponding measurements for a given GC to guide the eye. The four circled outliers are discussed in the text. Recent metallicity measurements have left the original relationship found by AZ88 essentially unchanged for [Fe/H] $\lesssim -0.4$ dex.
2.3. Analysis

GCs are HP 1 (Ortolani et al., 1997b), Terzan 1 (Ortolani et al., 1999a), Terzan 4 (Ortolani et al., 1997a; Origlia and Rich, 2004), and Terzan 9 (Ortolani et al., 1999b). All four are bulge GCs, therefore estimates of their metallicity are plagued by extinction and contamination by foreground bulge stars. In fact, as explained in the above respective references, it is possible that the CaT_{AZ88} measurements were contaminated by foreground metal-rich bulge stars. More particularly, as explained in Barbuy et al. (2006), the metallicity of HP1 is a matter of debate with metallicity estimates differing by as much as 1.2 dex. In any case, these four uncertain data points were not originally used by AZ88, leaving the relatively tight relationship essentially unaltered.

A linear fit to the updated data for the original 7 GCs selected by AZ88 (filled stars in Figure 2.7) yields results consistent with that of AZ88 within 1σ, indicating that more recent metallicity measurements have left the relationship unchanged. However, the most metal-rich GC (NGC 5927) used for this analysis has a metallicity of −0.4 dex and it is unclear whether the relationship remains linear beyond this point. Nevertheless, this confirms that it is still justified to obtain metallicities for Galactic GCs from the CaT_{AZ88} index measurements using the AZ88 relationship at least for $[Fe/H] \lesssim −0.4$ dex and possibly beyond.

2.3.2 Choice of index definition

Several index definitions for the CaT have been used in the literature. Among the definitions that apply to integrated spectroscopy are those of AZ88; Diaz et al. (1989, hereafter DTT89); and Cenarro et al. (2001, hereafter C01). For a review covering these index definitions and how they compare see C01. As mentioned above, AZ88 used integrated spectra of GCs to measure the CaT index. Their definition (CaT_{AZ88}) therefore should be suitable for GC integrated light spectra such as the present dataset. The CaT index definition of DTT89 (CaT_{DTT89}) is slightly broader, thus more suitable for the study of galaxy integrated light for which velocity dispersion broadens the CaT features. One drawback of this definition is that it uses the same two continuum passbands for all three CaT lines and is thus strongly affected by changes in the shape of the continuum. Because hot stars (B, A, and F types, blue horizontal branch or blue stragglers) have pronounced Paschen lines, three of which overlap with the CaT, one has to worry about contamination of
Chapter 2. Deriving Metallicities From the Integrated Spectra of Extragalactic Globular Clusters Using the Near-Infrared Calcium Triplet

Figure 2.8: Example of a fitted spectrum with the main spectral features highlighted. Identified spectral features include the CaT$_{F10}$ definition (Pa13, Pa15, and Pa16 lines overlap with the Ca3, Ca2, and Ca1, respectively), and the C01 Paschen ‘triplet’ lines (Pa17, Pa14, and Pa12). Three other metallicity sensitive lines are also highlighted (see Appendix B).

![Normalized flux vs Wavelength (Å)](image)

the CaT by Paschen lines from such stars. Therefore, when studying the behaviour of the CaT in a wide range of stellar temperatures the C01 definition (CaT$^*_{C01}$) may be preferable because it is designed to correct for the Paschen line contribution.

Provided that the GCs in NGC 1407 are comparable to their Galactic counterparts, one can use the empirical correlation obtained by AZ88 to obtain metallicities. The CaT$_{AZ88}$ index central passbands ($Ca1 = [8490.0-8506.0 \text{ Å}], Ca2 = [8532.0-8552.0 \text{ Å}], Ca3 = [8653.0-8671.0 \text{ Å}]$) were thus adopted for this work. As the typical velocity dispersion of GCs is small, the relatively narrow definition of AZ88 is appropriate. Also, contamination by Paschen lines should not be a concern for integrated spectroscopy of GCs because they are strong only in the theoretical spectra of young stellar populations ($\lesssim 2$ Gyr, but see Appendix B). Therefore, the passbands of the index definition of AZ88 were selected in order to use their empirical conversion to metallicity.

In Figure 2.8 we identify some of the features present in the CaT region of the spectrum. Our adopted definition of the CaT index is shown. Because the fitted spectra are continuum normalised, the continuum was set to unity to compute the fitted indices and the continuum passbands of AZ88 were not needed. The
2.3. Analysis

Figure 2.9: An assessment of the systematics introduced by our index measurement method. The x-axis shows the \( \text{CaT}_{\text{F10}} \) index value measured on the fitted spectra while the y-axis shows the same value measured using the \( \text{AZ88} \) index definition on the raw spectra. Black and grey points show values measured using old (> 8 Gyr) SSP model spectra from \( \text{V03} \) and our GC spectra with \( S/N \geq 15 \), respectively. The solid line shows the best fit line (\( \text{CaT}_{\text{AZ88}} = 0.783 \times \text{CaT}_{\text{F10}} + 0.96 \), see Equation 2.3) through the model points that is used to correct our index measurements.

CaT indices computed using this method will be referred to as \( (\text{CaT}_{\text{F10}}) \) in what follows. The continuum normalisation has introduced some systematic differences between our index values and those of \( \text{AZ88} \). Indeed, like flux calibration, continuum normalisation can cause systematic deviations that are difficult to quantify precisely without access to the original \( \text{AZ88} \) data (see \( \text{C01} \) for a discussion of this). In order to quantify the systematics we measure both the \( \text{CaT}_{\text{AZ88}} \) (i.e. measured on the raw spectra) and \( \text{CaT}_{\text{F10}} \) (i.e. after fitting) indices on the SSP models of \( \text{V03} \) for ages of 8 Gyr and older. Figure 2.9 shows the comparison, which has an offset but a very small scatter. The same is true for our GC spectra, albeit with larger scatter due mostly to the effects of skyline residuals on the measured \( \text{CaT}_{\text{AZ88}} \). The equation of the best-fit line to the \( \text{V03} \) SSP model points is:

\[
\text{CaT}_{\text{AZ88}} = (0.783 \pm 0.025) \times \text{CaT}_{\text{F10}} + (0.96 \pm 0.17),
\]

with \( r^2 = 0.97 \) implying that 97 per cent of the variability in the \( \text{V03} \) data is accounted for by the derived relationship. Combining with Equation 2.2 above
yields the following conversion between $CaT_{F10}$ and $[Fe/H]$:

$$[Fe/H]_{CaT} = -3.641 + 0.438 \times CaT_{F10}. \tag{2.4}$$

We will use Equation 2.4 to convert our $CaT_{F10}$ measurements into metallicities. Another potential source of systematics between our measured indices and those of AZ88 is the difference in resolution (corresponding to $\sigma = 51$ km s$^{-1}$ in our case). Fortunately, as shown in Figure 5b of C01, the relative measurement uncertainty induced by such a difference in resolution of $\sigma = 51$ km s$^{-1}$ for the $CaT_{AZ88}$ index is insignificant.

### 2.3.3 Single stellar population models

SSP models can provide theoretical insight for understanding the behaviour of the $CaT_{F10}$ index. Indeed, GCs are believed to be well approximated as SSPs. One should thus be able to directly compare GC properties with those of SSP models in the literature. Unfortunately, as will be demonstrated below, different SSP model sets make discrepant predictions about the behaviour of the $CaT_{F10}$ index with metallicity.

An advantage of using SSP models, particularly those providing spectral energy distributions (SEDs), is that it is possible to perform template fits and continuum normalisation in order to measure the $CaT_{F10}$ index so as to self-consistently directly compare the observed measurements with the model predictions. The present analysis is compared to the V03 and the BC03 SSP models, which both supply SEDs of sufficient spectral resolution.

Moreover, the V03 and BC03 models include photometry in the Johnson-Cousins system and a wide range of metallicities and ages. We use the V03 SSP models with a Kroupa (2001) initial mass function (IMF) and metallicities between $-1.68 \leq [Fe/H] \leq 0.02$. For the BC03 models, we use the SSPs with a Chabrier (2003) IMF (similar to the Kroupa IMF) in the metallicity range $-1.7 \leq [Fe/H] \leq 0.00$ so as to directly compare with the V03 models. Models with ages of 5, 9, and 13 Gyr are selected in both V03 and BC03.

Figure 2.10 shows the predictions of the V03 and BC03 models for $CaT_{F10}$ versus $(B - I)_0$ and metallicity. When no other independent metallicity measurement
Figure 2.10: Predictions from \texttt{V03} and \texttt{BC03} SSP models. The dotted, dashed, and solid lines correspond to 5, 9, and 13 Gyr models. From left to right, the red hollow circles on the \texttt{V03} model lines correspond to $[\text{Fe/H}] = -1.68, -1.28, -0.68, -0.38, 0.00, 0.02$ dex and the blue hollow diamonds on the \texttt{BC03} model lines correspond to $[\text{Fe/H}] = -1.7, -0.7, -0.4, 0.0$ dex. Our conversion between $\text{CaT}_{\text{F10}}$ and $[\text{Fe/H}]$ for $[\text{Fe/H}] \leq -0.4$ dex (Equation 2.4) is shown as a dashed gray line for comparison.

From Figure 2.10, we see that there is broad agreement between the \texttt{V03} and \texttt{BC03} SSPs in the overall range of the $\text{CaT}_{\text{F10}}$ values and its qualitative sensitivity to metallicity, though they differ greatly in the details. Indeed, the two different sets of models assign widely different metallicities to the same $\text{CaT}_{\text{F10}}$ value. A feature that is found in the \texttt{V03} models is the ‘loss of sensitivity’ or ‘saturation’ of the CaT
Chapter 2. Deriving Metallicities From the Integrated Spectra of Extragalactic Globular Clusters Using the Near-Infrared Calcium Triplet

features to metallicity as the metallicity increases beyond \([Fe/H] \sim [Fe/H]_{\text{CaT}} \sim -0.5\) dex for the \(~13\) Gyr model. This qualitative behaviour is in disagreement with that predicted by the BC03 models for which the \(CaT_{F10}\) sensitivity to metallicity appears to increase for higher values of \([Fe/H]\).

The effect of age on the measured \(CaT_{F10}\) index is minimal for old ages (e.g. DTT89, V03, Carrera et al. 2007). Indeed, as can be seen on Figure 2.10 both the V03 and BC03 models also predict very small variations of the \(CaT_{F10}\) for ages \(\gtrsim 5\) Gyr.

The empirical calibration of AZ88 (Equation 2.2), which is based on Galactic GCs, appears to lie below and above the V03 and BC03 models, respectively, in Figure 2.10. We note however that the slope of the V03 models at low metallicities ([Fe/H] \(\lesssim -0.5\) dex) is in good agreement with Equation 2.4. This was already shown in Figure 14 of V03.

In summary, we find that the BC03 and V03 models make discrepant predictions with respect to the behaviour of the CaT as a function of metallicity. For this reason, we choose to use the empirically derived conversion of AZ88 in this Chapter.

2.4 Results: The GC system of NGC 1407

NGC 1407 is a BGG showing clear GC colour bimodality with a division between the blue (metal-poor) and red (metal-rich) GCs occurring around \((B-I)_0 = 1.84\) or \((g-i)_0 = 0.93\) (see Harris et al. 2006; Forbes et al. 2006; R09). C07 obtained Keck/LRIS spectra of the brightest GC candidates. They derived metallicities and ages for 19 confirmed GCs and 1 ultra compact dwarf (UCD) using the Lick/IDS system (Gorgas et al. 1993; Worthey et al. 1994) and the method of Proctor et al. (2004). They found the majority to be old, with 3 being either young (i.e. \(~4\) Gyr) or old GCs with blue horizontal branches (hereafter young/BHB GCs). Figure 2.11 shows that the B00 relationship between colour and metallicity (derived for Galactic GCs) is also consistent with the NGC 1407 GC data. Noticeable in Figure 2.11 is the position of the 3 young/BHB GCs, which agrees with the 5 Gyr V03 model line. However, as mentioned in C07, their position could also be explained by the presence of a blue horizontal branch (BHB) in these clusters.

The results presented in Figure 2.7, 2.9 and 2.11 suggest that, under the as-
2.4. Results: The GC system of NGC 1407

Figure 2.11: Relationship between \([\text{Fe}/\text{H}]\) and colour for a sample of NGC 1407 GCs based on blue spectroscopic data from C07. The hollow circles highlight the 3 GCs identified in C07 as potentially young or harbouring BHBs while the triangles show common GCs between this work and that of C07. The solid black line shows the B00 relationship while the solid and dotted red lines represent the 13 and 5 Gyr V03 model predictions, respectively.

Assumption that the GCs in NGC 1407 are not significantly different from those of the Milky Way (i.e. similar stellar content), the \(CaT_{F10}\) index values should scale linearly with \((B-I)_0\) colours (at least for metallicities below \([\text{Fe}/\text{H}]\) \(\lesssim -0.5\) dex according to the V03 models). Figure 2.12 shows the relationship between the \((B-I)_0\) colours and \(CaT_{F10}\) for our sample of GCs. The \(CaT_{F10}\) values for the Milky Way GCs were converted from the \(CaT_{AZ88}\) quoted in AZ88. The agreement between the NGC 1407 dataset and the V03 models is good with the data scattering about the 13 Gyr track. While a general trend between colour and \(CaT_{F10}\) is observed, there are several interesting features present. Indeed, it appears as though the \(CaT_{F10}\) index flattens out or ‘saturates’ for metallicities higher than about \([\text{Fe}/\text{H}]\) \(\approx -0.5\) dex (on the right y-axis) as predicted by V03. This behaviour is in contradiction with the prediction of increasing metallicity sensitivity made by BC03 and with an extrapolation of the AZ88 relation to higher metallicities. We therefore decided to consider the V03 models more closely than the BC03 models as they yield better agreement.

The bulk of the GCs around NGC 1407 (and the V03 models) apparently have either higher \(CaT_{F10}\) index values, or bluer colours, than the Galactic GCs as shown...
Chapter 2. Deriving Metallicities From the Integrated Spectra of Extragalactic Globular Clusters Using the Near-Infrared Calcium Triplet

Figure 2.12: The distribution of NGC 1407 GCs in the \((B-I)_0-CaT_{F10}\) plane. Solid and dotted red lines are the V03 models for 13 and 5 Gyr, respectively. Young models of age 1.6 Gyr are also plotted as a solid grey line. Grey stars are Galactic GCs \((E(B-V) \leq 0.3)\) with colours taken from H96 and CaT_{F10} values from AZ88 (after applying the inverse of Equation 2.3). Squares show our data with relative sizes proportional to the signal-to-noise in the raw spectrum. Hollow symbols are discussed in Appendix B. The top x-axis shows the B00 colour-metallicity relationship based on Galactic GCs and the right y-axis shows the metallicity derived from CaT_{F10} using Equation 2.4. Typical uncertainties shown.

in Figure 2.12. This apparent offset between the Galactic GCs and the NGC 1407 GCs could be related to the lack of flux calibration in both this work and AZ88 which makes the two studies difficult to compare directly. Moreover, the small number and lack of redder Galactic GCs complicates this comparison. Also, the Galactic GCs are plagued by large photometric uncertainties due to Galactic extinction. Indeed, figure 14 of V03 has already shown that the behaviour of the CaT with metallicity in Galactic GCs is in reasonable agreement with their models. Because of the uncertainties involved, the relative position of the Galactic GCs along both axes of Figure 2.12 is uncertain and we refrain from drawing strong conclusions from it.

The GC metallicity distribution obtained by applying our CaT_{F10} to \([Fe/H]_{CaT}\) transformation (Equation 2.4) is shown in Figure 2.13. There are several unexpected features present in the inferred metallicity distribution. First, the blue tilt observed in the CMD (Figure 2.1) appears to still be present, however there is also a hint of an inverse red tilt. The spread in metallicity of the blue GCs seems to be wider than that of the red GC subpopulation in contrast to their spread in colour that
2.4. Results: The GC system of NGC 1407

is similar for both subpopulations. Moreover, using the $CaT_{F10}$ as a metallicity indicator seems to have merged the red and blue bright peaks even though they are separated in colour by more than $\Delta (g-i)_0 \approx 0.2$ or $\Delta (B-I)_0 \approx 0.25$ mag. This colour separation corresponds to an expected metallicity difference of over 0.8 dex for old ages (V03). Figure 2.14 shows the mean raw spectra of the brightest $(i < 20.5$ mag) red and blue GCs. They have similar CaT line strengths and hence inferred metallicity. The same exercise was repeated using the median value of the brightest spectra with, and without fitting, to ensure that the average was not biased by one outlier spectrum, skylines or our template fitting procedure. Each time there was no obvious difference between the strength of the CaT features in the bright red and blue GC spectra.

On the other hand, the averaging of the brightest red GCs has increased the signal-to-noise ratio sufficiently to detect the Mg I line at 8807 Å while this feature is barely present in the mean spectrum of the brightest blue GCs. We measure the generic Mg I index defined in Cenarro et al. (2009) for both spectra and find that the brightest red GCs have $Mg I = 0.77 \pm 0.13$ Å while the brightest blue GCs have $Mg I = 0.15 \pm 0.15$ Å. The Mg I line is mostly sensitive to both temperature and $[Mg/H]$ which correlates with $[Fe/H]$ (see Cenarro et al., 2009). This suggests that the bright blue GCs are either more typical of a hotter (earlier-type) or a less metal enriched stellar population than the red ones. The latter is more likely since hot stars contribute very little at near-infrared wavelengths.

At fainter magnitudes a difference in $CaT_{F10}$ is seen. The KMM test (Ashman et al., 1994) performed on the $CaT_{F10}$ inferred metallicities for the whole sample shows that a bimodal distribution is preferred over a unimodal one for this dataset at the 96 per cent confidence level. The output mean metallicities are $[Fe/H]_{CaT} = -1.20$ dex and $[Fe/H]_{CaT} = -0.61$ dex for the blue and red subpopulations, respectively. This can arguably be seen in the non-symmetric shape of the $[Fe/H]$ or $CaT_{F10}$ values histogram (see Figure 2.15). We are however careful drawing any strong conclusions from these results as: 1) the shape of the distribution seen in Figure 2.15 is considerably different from that seen in the colour histogram (Figure 2.3), and 2) the numbers are low. Moreover, the confidence level drops below significance (87 per cent only) when the KMM test is performed on the $CaT_{AZ88}$ index measured on the raw data possibly due to the larger measurement
Figure 2.13: The inferred metallicity distribution for our sample of NGC 1407 GCs. A running average (solid blue and red lines) have been overplotted for the blue and red subpopulations (colours are as inferred from the photometry). Typical uncertainties are shown (see Appendix A).

Figure 2.14: Averaged and continuum normalised raw spectra of the brightest ($i \leq 20.5$ mag) blue and red GCs in NGC 1407. The red spectrum has been shifted by 200 km s$^{-1}$ from a zero redshift for clarity. Even though their average $(g - i)_0$ colours are separated by over 0.2 mag, the CaT line strengths of the two mean raw spectra are nearly identical suggesting similar metallicities. This is in contrast with the MgI feature that is deeper in the red GCs as expected for higher metallicity.
2.5 Discussion

Figure 2.15: A histogram showing the distribution of the CaT$_{F10}$ (lower axis) and [Fe/H]$_{CaT}$ (upper axis) in our sample. The KMM test shows that the distribution of our data is best fitted with two Gaussians (overlaid) at the 96 per cent confidence level. The inferred mean metallicities are [Fe/H]$_{CaT} = -1.20$ dex and [Fe/H]$_{CaT} = -0.61$ dex for the blue and red subpopulations, respectively.

uncertainties. Nevertheless, with these caveats in mind, we compare with Forbes et al. (2006) who found an average of [Fe/H] = -1.45 dex and [Fe/H] = -0.19 dex for the metal-poor and -rich GC subpopulations based on (B − I)$_0$ photometry for NGC 1407 GCs. The inconsistently lower mean metallicity for the red subpopulation than that found in the analysis by Forbes et al. (2006) could be explained by: 1) possible radial gradients (see Section 2.2), and/or 2) the prediction of V03 of the saturation of the CaT feature around [Fe/H] $\sim$ -0.5 dex. However, it appears that the blue GC subpopulation has systematically higher measured CaT$_{F10}$ than expected. This cannot be attributed to either radial trends or saturation effects. It is puzzling that the absolute position of the blue GCs is shifted towards higher metallicities causing the two subpopulations’ metallicity distributions to be similar for the most luminous GCs.

2.5 Discussion

Based on the results presented in Figures 2.7, 2.9 and 2.11 the CaT$_{F10}$ index should scale linearly with metallicity and (B − I)$_0$ colour at least for [Fe/H] $\leq$ −0.4 dex.
On the other hand, SSP models disagree about the sensitivity and behaviour of the CaT features with respect to metallicity. The empirical calibration of AZ88 was adopted throughout this work to derive metallicities from the $CaT_{F10}$ index values under the assumption that the GCs around NGC 1407 are intrinsically similar to those around the Galaxy.

As demonstrated in Figure 2.14, the bright blue and red GCs in NGC 1407 have the same $CaT_{F10}$ index values. This would suggest that they have the same average metallicity even though they differ in mean ($g - i$)$_0$ colour by over 0.2 mag. The metallicity inferred from the AZ88 relationship for both the brightest blue and red GCs is $[Fe/H]_{CaT} \sim -0.8$ dex.

Moreover, even though the GC system is clearly bimodal in colour and in $CaT_{F10}$, which is measured on the fitted spectra, it is not bimodal in the $CaT_{AZ88}$ index distribution measured on the raw spectra. This is possibly due to increased measurement uncertainties of the indices measured on the raw spectra. For this reason, we do not consider that our CaT data are sufficient to confidently confirm (i.e. with more than 95 per cent confidence) that the GC system around NGC 1407 is bimodal in CaT inferred metallicity contrary to what is expected from the colours. However, in Appendix B we show how the distribution of the sum of the equivalent width of three weak features present in the fitted spectra only exhibit clear bimodality.

The disagreement between the metallicities inferred from the colours and those inferred from the $CaT_{F10}$ index values points to a fundamental difference between the GCs around NGC 1407 and the Milky Way either with respect to the behaviour of their colours or the $CaT_{F10}$ index with metallicity.

However, it is possible that the data have some systematic biases that could cause this behaviour. Such a systematic effect would need to affect the blue GC subpopulation much more than the red one. One possible source of systematics is the sky subtraction. If the sky was oversubtracted for the blue GCs only, this would yield higher $CaT_{F10}$ measurements. This was investigated and there is no obvious offset between the continuum levels of the blue and red subpopulations. The behaviour of the $CaT_{F10}$ with decreasing signal-to-noise was tested by adding Poisson noise to V03 SSP models SEDs of various metallicities. While lower signal-to-noise spectra inevitably yield to larger uncertainties on the measured $CaT_{F10}$ index values, no systematic scattering to higher or lower values, or with metallicity
or colour was found (see Appendix A).

Assuming the data are reliable we now explore several possible explanations. One possible explanation to the similar metallicities inferred for the bright blue and red GCs is that the CaT features saturate at lower metallicities than predicted by the SSP models (i.e. at \([Fe/H]_{\text{CaT}} \sim -0.8\) instead of \([Fe/H]_{\text{CaT}} \sim -0.5\) dex). If we make the reasonable assumption that our composite near-infrared spectra are not significantly influenced by hot early-type stars, the presence of a stronger Mg\(I\) line in the mean spectrum of the bright red GCs than in that of the bright blue GCs does indeed suggest that the \(CaT_{F10}\) could be saturated while the Mg\(I\) is still sensitive to metallicity. However, the data presented in Figure 2.12 suggests a saturation metallicity that is in agreement with the \(V03\) models. Nevertheless, early saturation of the \(CaT_{F10}\) could happen if the GCs around NGC 1407 were Calcium enhanced with respect to their Galactic counterparts (i.e. \([Ca/Fe]\) is larger in NGC 1407 GCs). Indeed, the data presented in Battaglia et al. (2008) for the CaT in individual red giant branch stars suggests that a different \([Ca/Fe]\) ratio than is present in the calibration GCs may influence the measured CaT values and thus the inferred metallicities by up to about 0.2 dex uncertainty for \([Fe/H]\).

A saturation of the CaT features at lower metallicities could also be the result of a more bottom-heavy IMF for the GCs around NGC 1407 with respect to those around the Galaxy. Because the \(CaT_{F10}\) index decreases with increasing surface gravity (DTT89; Cenarro et al. 2002), dwarf stars have lower CaT values. A stellar population with a bottom-heavy IMF would contain a larger proportion of dwarf stars at old ages and thus should saturate at lower \(CaT_{F10}\) index compared to a more top-heavy IMF. For example, models with a Salpeter (1955) IMF saturate at higher \(CaT_{F10}\) values than models with a Kroupa (2001) IMF in the \(V03\) SSP models. The Mg\(I\) index is only minimally influenced by gravity (Cenarro et al. 2009), so it is unlikely to be significantly influenced by a different IMF and should still be a good tracer of metallicity.

The relative spread in \(CaT_{F10}\) inferred metallicity of the blue and red subpopulations are at odds with what is expected from their respective spread in colour. If proven correct, this could be due to the non-linearity of the conversion between colours and metallicity (e.g., Yoon et al. 2006; Peng et al. 2006). In some galaxies, a non-linear conversion between colour and metallicity could cause a unimodal
metallicity distribution to appear bimodal in colour \cite{Cantiello and Blakeslee 2007}. Therefore, if we take our inferred metallicities at face value, the colour and metallicity distributions could be reconciled by invoking this effect.

Alternatively, the difference in the relative spreads of the respective subpopulations between the colour and \( CaT_{F10} \) distributions could be a result of systematic biases. Indeed, the higher sensitivity of the \( CaT_{F10} \) to metallicity for metal-poor (blue) GCs, which have metallicities lower than the saturation limit predicted by V03, allows for a wider range of inferred metallicities. However, the saturation limit is reached at metallicities corresponding to the metal-rich (red) GCs. This in turn reduces the range of allowed \( CaT_{F10} \) values and thus the inferred range in metallicities for the red GC subpopulation.

It is possible, although an extreme case, that the majority of our blue spectra are contaminated by Paschen line absorption. If this were true it could play a definite role in explaining our inferred metallicity distribution. There are several spectral features of the Paschen series of hydrogen in the spectral region of the CaT. Their individual depths vary slightly with the deepest lines at redder wavelengths. Because three of the features of the Paschen series of Hydrogen overlap with the three CaT features, even a small level of contamination or order \( \approx 0.3 \) Å per overlapping Paschen line would be sufficient to significantly alter the measured \( CaT_{F10} \) index by \( \approx 0.9 \) Å. Paschen lines are predominant in stellar spectra of B, A, and F spectral types. These usually massive hot stars are short lived and thus old stellar populations such as GCs are not expected to show significant Paschen absorption features from such stars. Indeed, Paschen lines only become significant in the V03 SSP models for ages \( \lesssim 2.0 \) Gyr and metallicities \([Fe/H]\) \( \lesssim -0.68 \) dex. However, keeping in mind that models are uncertain at young ages (V03), we cannot rule out the possibility these GCs could be young. Non-overlapping Paschen lines around the CaT (i.e. Pa12, Pa14 and Pa17) with equivalent widths of order \( \approx 0.3 \) Å would not be detectable in our modest signal-to-noise spectra. However, in Appendix B we discuss how Paschen lines are sometimes visible in the fitted spectra only.

Another alternative is a population of GCs with hot blue stars such as BHB or blue straggler (BS) stars \cite{Cenarro et al. 2008b} at intermediate metallicities. This is consistent with the favoured conclusion of C07 regarding the young/BHB GCs in NGC 1407 based on the diagnostic of Schiavon et al. \cite{2004}. Moreover,
2.5. Discussion

there is some evidence from UV studies that the GC systems of massive E galaxies such as NGC 1407 could harbour a significant population of GCs with extreme hot horizontal branches (see Sohn et al., 2006; Mieske et al., 2008). We examined the archival GALEX UV images of NGC 1407 and found that they were not deep enough for its GC system to be detected. If an additional contribution from Paschen line to the $CaT_{F10}$ index caused by hot blue stars is indeed present, then NGC 1407 could harbour a population of intermediate metallicity GCs with BHBs or extreme HBs as speculated from UV studies of other galaxies or a population of GCs with a large proportion of BS stars.

With this in mind, it is worth reconsidering Figure 2.11 and the results of C07. The $(r-i)_0$ colours should be less affected by, although not immune to, the presence of hot blue stars. This is because hot blue stars contribute less of the integrated light at redder wavelengths (e.g., Smith and Strader, 2007; Spitler et al., 2008a; Cantiello and Blakeslee, 2007). We therefore compare the position of the 3 young/BHB GCs identified by C07 in both colour spaces. The position of the 3 young/BHB GCs are consistent with the bulk of the other GCs with measured old ages using $(r-i)_0$ colours (right hand panel of Figure 2.11).

In summary, the unexpected distribution of $CaT_{F10}$ values and inferred metallicities for NGC 1407 GCs could be explained by 1) early saturation of the CaT features in NGC 1407’s GCs, 2) a population of GCs with hot blue stars in NGC 1407, and/or 3) the non-linear conversion between colour and metallicity. With the dataset presented in this Chapter and based on the current generation of SSP models at near-infrared wavelengths, we cannot positively determine which (combination) of these possible explanations is the correct one. Unfortunately, this casts serious doubts on the $CaT_{F10}$ inferred metallicity distribution shown in Figure 2.13, the presence of a spectroscopic blue tilt, and the potential of the NIR CaT feature as a metallicity indicator in the integrated light spectra of extragalactic GCs. Until these issues are understood, metallicities inferred from the $CaT_{F10}$ for integrated light spectroscopy of extragalactic GCs will remain uncertain. We return to this issue in Chapter 5.
Chapter 2. Deriving Metallicities From the Integrated Spectra of Extragalactic Globular Clusters Using the Near-Infrared Calcium Triplet

2.6 Summary

The empirical relationship found by Armandroff and Zinn (1988) between the CaT$_{AZ88}$ index values and metallicities in Galactic GCs was revisited in the light of more recent metallicity measurements. No noticeable difference was found and based on the literature we conclude that the CaT can in principle be used to determine metallicities in integrated spectroscopy of extragalactic GCs. This assumes that the Galactic GCs are not intrinsically different from extragalactic GCs.

We also compare the predictions for the behaviour of the CaT$_{F10}$ with metallicity for the V03 and BC03 SSP models. We find that different SSP model sets assign widely different absolute metallicities for a given CaT$_{F10}$ value.

A sample of 144 GCs in NGC 1407 suitable for stellar population analysis were obtained in the spectral region near the CaT using DEIMOS on Keck. The metallicity distribution for this sample was obtained based on the empirically determined conversion of AZ88 from CaT$_{AZ88}$ index values. Several unexpected results were obtained, the most notable of which is the identical CaT$_{F10}$ index values for the brightest blue and red GCs. Even though the bright red and blue GCs are well separated in colour space, the CaT$_{F10}$ measurements suggest that they have a similar metallicity. We show that this result is independent of the index measurement method used since the average raw spectra for the brightest blue and red GCs themselves are nearly identical.

Integrated light spectra of nearby (Local Group) resolved GCs with independently measured ages, metallicities and HB morphologies determined via colour-magnitude diagrams are essential to determine what effects metallicity, age, HB stars or BS stars have on the integrated light spectra of GCs in the near-infrared. Such a dataset would also help disentangle the influence of bright blue stars and/or age from those of metallicity on NIR spectra around the CaT. Furthermore, it would allow a robust calibration of the CaT$_{F10}$ index as a reliable metallicity indicator for unresolved extragalactic GCs.
3

Metallicity Gradients at Large Galactocentric Radii Using the Near-infrared Calcium Triplet

3.1 Introduction

In this Chapter, we present a pilot study in which we extend the Stellar Kinematics with Multiple Slits (SKiMS) technique developed by P09 to measure metallicity gradients out to large galactocentric radii for 3 giant ETGs (NGC 1407, NGC 2768 and NGC 4494). Following P09, we extract near-infrared (NIR) spectra of the galaxy stellar light at large galactocentric radii using the DEIMOS multi-object spectrograph on Keck. The DEIMOS spectrograph is most efficient in the NIR where the CaT spectral feature dominates. As mentioned in Chapter 2, the CaT has been shown to correlate with metallicity (e.g., AZ88; DTT89; C01) with little age sensitivity (e.g., DTT89; Schiavon et al. 2000; Cole et al. 2004; Carrera et al. 2007; V03). We use the CaT together with the single stellar population (SSP) models of V03 to develop a new technique for deriving metallicity gradients using DEIMOS reaching as far out as \( \sim 2r_e \). This technique can be applied to a large sample of galaxies and compared to the predictions of galaxy formation scenarios.

The present Chapter is divided as follows: in Section 3.2 and 3.3 we give a brief description of our sample galaxies and an overview of our data, respectively. In Section 3.4 we explain the method used to extract metallicities and in Section 3.5
we give our results. Finally, Sections 3.6 and 3.7 contain a discussion of our results and a summary, respectively.

3.2 Sample

A summary of the relevant properties of our sample galaxies is given in Table 3.1. Digitized Sky Survey (DSS) images are shown in Figure 3.1. Below we give a brief overview of each galaxy.

3.2.1 NGC 1407

As mentioned in Chapter 2, NGC 1407 is the brightest group galaxy that dominates the Eridanus A group (Brough et al., 2006). It is a giant E galaxy with a clear core-like luminosity profile (Spolaor et al., 2008a). It has been measured to have a
### Table 3.1: Galaxy properties.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Hubble Type</th>
<th>P.A. (deg)</th>
<th>Axis ratio</th>
<th>Distance (Mpc)</th>
<th>$r_e$ (arcsec)</th>
<th>$M_B$ (mag)</th>
<th>$M_K$ (mag)</th>
<th>Stellar mass ($10^{11} M_\odot$)</th>
<th>$V_{sys}$ (km s$^{-1}$)</th>
<th>$\sigma_0$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1407</td>
<td>E0</td>
<td>60</td>
<td>0.95</td>
<td>26.8</td>
<td>70</td>
<td>-21.4</td>
<td>-25.4</td>
<td>2.86</td>
<td>1782</td>
<td>272.5</td>
</tr>
<tr>
<td>NGC 2768</td>
<td>S0$_{1/2}$</td>
<td>93</td>
<td>0.46</td>
<td>20.8</td>
<td>64</td>
<td>-20.9</td>
<td>-24.6</td>
<td>1.37</td>
<td>1327</td>
<td>181.8</td>
</tr>
<tr>
<td>NGC 4494</td>
<td>E1-2</td>
<td>173</td>
<td>0.87</td>
<td>15.8</td>
<td>49</td>
<td>-20.4</td>
<td>-24.8</td>
<td>1.64</td>
<td>1335</td>
<td>150.2</td>
</tr>
</tbody>
</table>

Position angles and axis ratios (columns 3, 4) are from 2MASS. Distances (column 5) are based on surface brightness fluctuations Tonry et al. (2001) and include the distance moduli correction of Jensen et al. (2003). Effective radii (column 6) are taken from the Third Reference Catalogue of Bright Galaxies (RC3, de Vaucouleurs et al. 1991). $B$- and $K$-band absolute magnitudes (columns 7, 8) are calculated from RC3 and 2MASS apparent magnitudes, respectively, and using the distances quoted in column 5. Stellar masses (column 9) are calculated from the $K$-band magnitude of column 8 assuming a $M/L_K$ ratio corresponding to the V03 SSP of age 10 Gyr and solar metallicity. Systemic velocities (column 10) are from P09. Central velocity dispersions (column 11) are as per Paturel et al. (2003).
uniform old age with a steep metallicity gradient and high $\alpha$-element ratio within one effective radius \citep{Spolaor2008}. In their study of the stellar kinematics, \cite{Spolaor2008} found tentative signs of a kinematically decoupled core (KDC) at the centre of NGC 1407. However, as they point out this KDC detection may be spurious and due to a possible misalignment of the slit with the semi-major axis of the galaxy. Nevertheless, if confirmed, the presence of a KDC in the centre of NGC 1407 may be the signature of a merger history. Otherwise, it shows little sign of fine structure or recent disturbance.

### 3.2.2 NGC 2768

The literature is not unanimous with regards to the morphological classification of NGC 2768, which ranges from E \citep{deVaucouleurs1991} to S0 \citep{Sandage1981, Sandage1994}. Evidence of rotation has been found by several authors \citep{Fried1994, Emsellem2004, P09} as well as the presence of a centrally concentrated kinematic twist \citep{McDermid2006}. NGC 2768 is located at the centre of a loose group of which it is the brightest galaxy \citep{Giuricin2000}. No previous metallicity gradient measurement is available, however the measured central metallicity varies from $[\text{Fe}/\text{H}] \approx -0.2$ to $+0.3$ dex \citep[see][]{Howell2005, Denicol2005, Silchenko2006}. The literature is also discrepant with respect to its central age with ages ranging between 8 and 15 Gyr \citep[e.g.,][]{Howell2005, Denicol2005, Silchenko2006} possibly because of different spatial sampling.

### 3.2.3 NGC 4494

NGC 4494 is classified as an E galaxy located in the Coma I cloud \citep{Forbes1996, Larsen2001}. Its luminosity profile displays a central cusp \citep{Lauer2007}. It has a KDC \citep{Bender1988}, an intermediate central age of 6.7 Gyr and a central metallicity of $[\text{Fe}/\text{H}] \approx +0.03$ dex \citep{Denicol2005}. For these reasons, it is considered a good candidate for a possible gas-rich merger remnant \citep[hereafter H09]{Hopkins2009}.
3.3 Data

3.3.1 Acquisition

Our main observing program was to obtain spectra for GC systems around ETGs. A total of 5 ETGs have been observed so far (see P09, for details). From this initial sample, we selected 3 galaxies that had the greatest number of spectra and highest quality (signal-to-noise ratio).

Spectra were obtained using the DEIMOS spectrograph on the Keck telescope during the nights of 2006 November 19-21, 2007 November 12-14 and 2008 April 8. The seeing was good (typically ∼ 0.7 arcsec). The 1200 1 mm$^{-1}$ grating was used with a central wavelength of either 7500 Å (2006 Nov.) or 7800 Å (2007 Nov., 2008 Apr.). In every case, the setup allowed for the coverage of the CaT region (∼ 8400 – 8900 Å) with a resolution of Δλ ∼ 1.5 Å (FWHM) for the 1” slit width. A total of 6, 2 and 3 multi-slit masks were observed for NGC 1407, NGC 2768 and NGC 4494, respectively. The typical total exposure time on each mask for NGC 1407 and NGC 2768 was 2 hours (4 × 30 minutes exposures) and 1.5 hours (3 × 30 minutes exposures) for NGC 4494. One mask for NGC 2768 was observed for 1 hour on two separate nights yielding two independent measurements. Figure 3.1 shows our selected galaxies together with the positions of the selected slits (see Section 3.3.2 for the selection process).
3.3.2 Reduction

The DEIMOS data were reduced using the IDL spec2d data reduction pipeline written for the DEEP2 galaxy survey. An overview of the reduction steps performed by the pipeline is given in Section 2.2.2. Residual fringing is negligible due to instrumental design (e.g., Faber et al., 2003; Wirth et al., 2004). In addition to the sky subtracted GC spectra, the pipeline produces several outputs, among which are the background (or ‘sky’) spectra.

We used the SKiMS technique of P09 to extract galaxy stellar light spectra out of the background spectra. The background spectra are essentially the sum of both sky and galaxy light. P09 use an appropriately scaled ‘true’ sky spectrum that is then subtracted from the background spectrum to extract the sky subtracted galaxy stellar light spectrum.

In this thesis, we compute the scaling factor on the raw background spectra as the excess flux in the region 8605.0-8695.5 Å above a linear continuum determined from two carefully selected sidebands that avoid both strong skylines and galaxy spectral features for each galaxy (see Table 3.2). Figure 3.2 shows an example background spectrum together with the definition of the sky scaling factor. As can be seen in Figure 3.2, the recession velocity of NGC 2768 (and NGC 4494) causes the Ca3 line to be partly redshifted into the central passband of the sky index. This could introduce systematic uncertainties when applying the sky subtraction. To test this, we use a slightly narrower central passband avoiding the Ca3 feature and find no noticeable changes to our results. Thus, because small variations in instrument resolution and wavelength solution across the mask could cause the minima between the individual skyline peaks to vary and introduce uncertainties if the edge of the sideband is near a strong skyline we choose to use the same central band definition for all three galaxies in our sample.

The ‘true’ sky is derived from the normalised sum of several background spectra at very large galactocentric radii (6-7$r_e$). Even at 6-7$r_e$, there is still some galaxy background light in our sky estimate. However, using a de Vaucouleurs (1953) luminosity profile, we estimate that the galaxy light in these outer sky spectra is at most 6 per cent of the galaxy light in our science spectra. We use Monte Carlo methods to evaluate the accuracy of the sky subtraction at 9 signal-to-noise intervals.
ranging from 10 to 50 and find that the uncertainty in the final continuum level introduced by over/undersubtracting the sky is negligible compared to the noise (0.7 per cent of the level of the noise for our lowest signal-to-noise ratio) if a linear continuum is assumed as is typical in this spectral region. The method described in [P09] is similar to that of Norris et al. (2008) and Proctor et al. (2008), which employed background spectra from Gemini/GMOS and Keck/LRIS, respectively. For further information on the sky subtraction method used herein see [P09].

Next, the galaxy stellar light spectra were fitted using the pPXF code of Cappellari and Emsellem (2004) to extract stellar kinematics out to large galactocentric radii ($\lesssim 3r_e$). The kinematics are presented in [P09]. In Figure 3.3, we show examples of the extracted galaxy stellar light spectra and highlight regions that are still contaminated by skyline residuals. We find that approximately 10 per cent of the amplitude of these skyline residuals can be attributed to small variations of the wavelength solution across the mask. The remaining fraction is likely caused by the inherent complications associated with non-local sky subtraction due to variations of the sky spectrum over time and across the large field of view. As noted in [P09], the strong skyline residuals are not significantly larger than the Poisson noise associated with them. Because of these skyline residuals, our method yields better results for galaxies with systemic recession velocities that do not cause the CaT features to be shifted into skyline dominated regions (i.e., $500 \text{ km s}^{-1} \lesssim V_{\text{sys}} \lesssim 1400 \text{ km s}^{-1}$ or $1700 \text{ km s}^{-1} \lesssim V_{\text{sys}} \lesssim 2500 \text{ km s}^{-1}$). Due to the inherent difficulties associated with flux calibrating multi-slit data our spectra are not flux calibrated.

Finally, we select our highest signal-to-noise spectra by removing any spectra with an average number of counts per angstrom $< 73$. This roughly corresponds to a signal-to-noise cut of 8.5.

### 3.4 Analysis

#### 3.4.1 Index Measurements

There are several CaT index definitions that apply to integrated light spectra. The choice of index definition is somewhat dependent on the purpose one desires to fulfil. Indeed, [AZ88] used narrow central passbands for the CaT to determine an
empirical conversion between their CaT index and metallicities using the integrated light spectra of Galactic GCs. A year later, DTT89 defined a much broader index, which they applied to the integrated light spectra of galaxies for which line indices are broadened due to their large velocity dispersion. The major drawback of this definition is that it uses the same continuum passbands for all three CaT lines and is therefore very sensitive to variations in the shape of the continuum. In the work of C01, this is circumvented by the possibility of using an arbitrary number of continuum passbands. Also, in order to reduce the effects of skylines and other non-Poisson noise during the CaT index measurement, the method of C01 weighs each pixel according to its variance. Moreover, the three features that constitute the CaT (i.e., Ca1, Ca2 and Ca3) have different relative depths with the bluest (Ca1) being the weakest. For this reason, some authors have decided to give varying weights to the different CaT features or to remove the Ca1 feature altogether from their CaT index definition (e.g., Armandroff and Da Costa, 1991; Rutledge et al., 1997a; Koch et al., 2006, 2008).

Because we are using velocity dispersion broadened galaxy spectra in this Chapter, we cannot use the narrow AZ88 central passbands definition or their empirical

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**Figure 3.2**: Example of a background spectrum (i.e., galaxy light + sky) for NGC 2768. Labelled grey shaded regions highlight the continuum and central passbands of the sky scaling index definition. The dashed line shows the continuum estimate derived for this particular spectrum (the sky subtracted spectrum is shown in the top panel of Figure 3.3). Positions of galaxy individual CaT features are labeled.
Figure 3.3: Examples of a high (top panel), typical (middle panel) and low (bottom panel) signal-to-noise galaxy stellar light spectra for NGC 2768. The raw spectra are shown as the black solid line. Grey highlighted regions show spectral ranges contaminated by skylines. Selected spectra have average number of counts per angstrom \( \geq 73 \).
conversion like we did in Chapter 2. We thus choose to adopt the DTT89 index central passbands definition with the continuum determination and index measurement technique described in C01. The central passband definitions as well as the continuum passbands of our CaT index are given in Table 3.3 and Figure 3.4. We also employ a weighted sum such that:

\[ \text{CaT} = 0.4 \times \text{Ca1} + \text{Ca2} + \text{Ca3}. \] (3.1)

This is done in order to minimize the impact of the more uncertain Ca1 feature. The continuum passbands are chosen to uniformly cover the spectral range around the CaT features and in such a way as to avoid large spectral features and regions dominated by skyline residuals. The weights on the individual CaT features in Eq. 3.1 are chosen to minimize the estimated uncertainties on the CaT index values. Uncertainty estimates are computed using the background spectra (i.e., before sky subtraction) instead of fully propagated variance arrays, which are unavailable as our spectra are not processed within the data reduction pipeline. The background spectra provide a good estimate of the true variance since the bulk of the variance is caused by skylines, which in turn yields a robust uncertainty estimate. The technique described in Cardiel et al. (1998) and C01 (appendix A2) for generic indices is used. Finally, we apply a velocity dispersion correction in order to obtain CaT index values that are comparable to those measured at the models’ dispersion. This correction is shown in Figure 3.5. For both NGC 2768 and NGC 4494, the velocity dispersions were taken from P09. However, the velocity dispersion profile of NGC 1407 measured by P09 reveals a sharp ‘spike’ around \( r \sim 0.9r_e \). The high velocity dispersion values measured from the corresponding slits (highlighted in white in Figure 3.1) produce high CaT index values. These in turn yield highly deviant (unphysical) metallicities of up to \([Fe/H] \sim 2.0\) around \( r \sim 0.9r_e \). The cause of this ‘spike’ in the velocity dispersion profile is unknown. Because the required velocity dispersion correction is clearly too large, we adopt velocity dispersion values extrapolated through the ‘spike’ by assuming a smoothly declining velocity dispersion profile as typical of E galaxies.

We also test for the effect of higher order velocity moments \((h_3 \text{ and } h_4)\) on the measured CaT index values. We find that for reasonable values of \(-0.2 < h_3 < 0.2\)
3.4. Analysis

<table>
<thead>
<tr>
<th>Feature</th>
<th>Weight</th>
<th>Central passband (Å)</th>
<th>Shared continuum passbands (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca1</td>
<td>0.4</td>
<td>8483.0-8513.0</td>
<td>8474.0-8483.0</td>
</tr>
<tr>
<td>Ca2</td>
<td>1.0</td>
<td>8527.0-8557.0</td>
<td>8514.0-8526.0</td>
</tr>
<tr>
<td>Ca3</td>
<td>1.0</td>
<td>8647.0-8677.0</td>
<td>8563.0-8577.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8619.0-8642.0</td>
<td>8619.0-8642.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8680.0-8705.0</td>
</tr>
</tbody>
</table>

Table 3.3: \( CaT_{F09} \) index definition.

and \(-0.2 < h_4 < 0.2\), the measured CaT value varies by up to ±0.1 and ±1 Å, respectively. While variations induced by high values of \( h_3 \) are comparable to our typical measurement uncertainties, the same is not true for \( h_4 \). Unfortunately, we do not measure \( h_3 \) or \( h_4 \) accurately enough to reliably correct for this effect. We thus mention the potentially important effect of higher order velocity moments on the measured CaT index as a possible caveat of this method.

The uncertainties on the CaT index values are propagated accordingly and include uncertainties in the respective velocity dispersion measurements. Because of the non-linear nature of the velocity dispersion correction, large velocity dispersions yield larger CaT index uncertainties. Finally, we estimate that sky subtraction random uncertainties contribute at most 0.001 Å, which is minimal compared to our measured typical random uncertainties. Larger systematics may arise from the skyline residuals as described in Section 3.3.2. These are alleviated and partly accounted for via weighting according to the C01 index measurement method. In what follows we will refer to the CaT index measured using the above method as \( CaT_{F09} \).

In order to facilitate comparison with previous studies, we use the V03 SSPs with 13 Gyr to derive a conversion between our \( CaT \) and the similar CaT index defined by DTT89 (\( CaT_{DTT89} \)). We obtain the following:

\[
CaT_{DTT89} = 18.0 - 7.0 \times CaT_{F09} + 0.86 \times CaT_{F09}^2,
\]

with a standard deviation of \( \sigma = 0.25 \) Å.
Chapter 3. Metallicity Gradients at Large Galactocentric Radii Using the Near-infrared Calcium Triplet

Figure 3.4: Representation of the CaT definition used in this Chapter (CaT$_{F09}$). The solid line spectrum is a V03 SSP model with [Fe/H] = −0.68 and age of 13 Gyr broadened to 150 km s$^{-1}$ dispersion to mimic the effect of a typical galaxy’s velocity dispersion. Labelled grey shaded regions represent the CaT and continuum passbands. The dashed line shows the continuum level estimated using the method of C01.

Figure 3.5: Applied velocity dispersion index correction. The correction was obtained by comparing our index measured directly on the V03 SSP spectra of ages 13 Gyr (CaT$_{F09}$) and on the same spectra convolved with Gaussians of corresponding widths for a given velocity dispersion (CaT$_{F09,\sigma}$). The shaded area shows the expected scatter in the correction caused by the different model metallicities. The solid line shows the best fit polynomial of third order through the median metallicity (i.e., [Fe/H] $\sim$ −0.28 dex) model points.
3.4.2 Conversion into metallicities

We use SSP models of V03 with the Kroupa (2001) IMF in order to convert our $CaT_{F09}$ measurements into metallicities. There are two main reasons that motivated this choice. First of all, the V03 models provide spectral energy distributions (SEDs) at a resolution comparable to that of our data. Moreover, the V03 models show good agreement with Galactic GC data (see Figure 14 of V03). We assume a constant age of 13 Gyr to convert $CaT_{F09}$ into metallicity. The predictions of the V03 models cover metallicities ranging from $-1.68$ dex $\leq [Fe/H] \leq +0.2$ dex (corresponding to $4.1 \lesssim CaT_{F09} \lesssim 6.2$ Å). Outside this range, the behaviour of the $CaT_{F09}$ with metallicity is not constrained. This can be a serious issue particularly at high values of $CaT_{F09}$ and $[Fe/H]$, where the conversion is steepest. For this reason and to avoid the introduction of uncertainties related to model extrapolation, we apply a hard boundary such that metallicities derived from data points that have measured $CaT_{F09} \geq 6.2$ Å are discarded and assigned the maximum metallicity (i.e., $[Fe/H] = 0.2$ dex). These points are clearly identified in the plots that follow and are not used in subsequent analyses. Uncertainties are propagated from the $CaT_{F09}$ uncertainties. Once again, the non-linearity of the derived conversion from $CaT_{F09}$ into metallicity yields larger uncertainties at high metallicities. We also make use of rolling averages with radius as they are more robust against random fluctuations.

There could be other sources of uncertainty. First, there could be hot blue stars such as young, BHB or BS stars contaminating the CaT with their predominant Paschen line features (see C01). Unfortunately, varying BHB morphologies and BSs are not modeled by V03 and one has to worry about possible contamination by hot blue stars when converting $CaT_{F09}$ into metallicities as three of the features in the Paschen series of hydrogen overlap with the three CaT lines. However, we visually inspected our spectra and find that there is no indication for the presence of a Paschen line at 8751 Å where it should be most easily seen.

Another source of uncertainty in our conversion into metallicities has to do with the effect of age on the CaT feature. Fortunately, the CaT is only minimally influenced by age effects for ages $\gtrsim 2.5$ Gyr (e.g., DTT89; Schiavon et al. 2000; V03; Cole et al. 2004; Carrera et al. 2007). This is in apparent contradiction with the predictions of the V03 models shown in Figure 3.6. On the other hand, it is likely
Chapter 3. Metallicity Gradients at Large Galactocentric Radii Using the Near-infrared Calcium Triplet

Figure 3.6: Single stellar population model predictions for 13, 9 and 5 Gyr (solid, dashed and dotted lines, respectively) from V03. The spectral resolution is $\Delta \lambda \sim 1.5\,\text{Å}$. The 5 Gyr model data are uncertain for metallicities $[\text{Fe/H}] = -1.28$ and $-1.68$ dex.

that different CaT index definitions could yield different age dependencies as is often the case for other spectral features. Thus, it is conceivable that the apparent age trends seen in Figure 3.6 may be influenced by our choice of index definition. Nevertheless, if we ignore the points corresponding to the 5 Gyr models with metallicities $[\text{Fe/H}] = -1.68$ and $-1.28$ dex that V03 consider unreliable due to a lack of corresponding stars in the stellar library, the maximum uncertainty on the inferred metallicity induced by wrongly using a 13 Gyr old SSP to estimate metallicity in a 5 Gyr SSP is insignificant, as expected from observational studies. Therefore, because the inner parts of our galaxies are measured to be much older than 2.5 Gyr, age effects should not strongly influence our inferred metallicities.

3.5 Results

The spatial distribution of slits on the DEIMOS mask was optimised for the study of GCs. For this reason, the position from where our stellar light spectra are extracted are distributed in a somewhat ad hoc manner around a given galaxy. In order to present our results in a way that is comparable to previous measurements (i.e., along the major or minor axes), we transform our galactocentric radii values into their spherical equivalent if the slit lies along the semi-major axis. To do this, we
first define the effective change in right ascension and declination as

\[ \Delta \alpha = (\alpha_{\text{slit}} - \alpha_{\text{galaxy}}) \cos \delta_{\text{galaxy}}, \quad \text{and} \]
\[ \Delta \delta = \delta_{\text{slit}} - \delta_{\text{galaxy}}; \]

respectively; where we have implicitly used the small-angle approximation. The subscripts ‘slit’ and ‘galaxy’ correspond to the position of the slit and the photometric centre of the galaxy in equatorial coordinates, respectively. Next we use the photometric axis ratio \( q_{\text{phot}} \), position angle \( \phi \), and \( r_e \) from the literature (see Table 3.1) to convert the ‘true’ distance to the centre of the galaxy into a pseudo major-axis distance. Or mathematically, we apply the following formula:

\[ \left( \frac{r}{r_e} \right) = \sqrt{\left( \frac{\Delta \alpha'}{q_{\text{phot}}} \right)^2 + (\Delta \delta')^2} r_e, \]

where \( \Delta \alpha' = (\Delta \delta) \cos \phi + (\Delta \alpha) \sin \phi \), and \( \Delta \delta' = -(\Delta \alpha) \cos \phi + (\Delta \delta) \sin \phi \). Assuming that there is no significant change in metallicity along isophotes, our results should be comparable to the literature’s values for slits aligned with the semi-major axis. If this assumption is partly incorrect, for example due to possible multiple stellar components, which may be the case for disky galaxies such as NGC 2768, it will introduce scatter in the metallicity at a given radius. In what follows, all galactocentric radii have been obtained with this method.

We plot the rolling average using 8 to 10 points depending on the size of the dataset in Figure 3.7, 3.8, and 3.9. The rolling average gives a clearer indication of the actual shape of the metallicity gradient in our galaxies by eliminating the confusion caused by the scatter due to random uncertainties on our data points. We find that the slope of the CaT\textsubscript{F09} and metallicity gradients changes with galactocentric radius and thus cannot be appropriately described as linear in log-log space. This makes their objective quantification difficult.

The quantification of the metallicity gradient in the inner regions of galaxies using the slope of a fitted line in log-log space has been useful in previous works to quantify the steepness of the gradient and constrain theoretical models (e.g., Spolaor et al., 2009; Kobayashi and Arimoto, 1999). However, we do not fit linear relations to our metallicity gradients as this does not quantify them properly. Instead, we
Figure 3.7: CaT$_{F09}$ (top panel) and metallicity (lower panel) gradients for NGC 1407. The stars are from the long slit data presented in Spolaor et al. (2008b) and the filled circles represent our data. Upper arrow uncertainties are used when the CaT$_{F09}$ is beyond the upper limit (thin dashed lines) of the V03 SSP models. Thick solid lines are rolling averages. Profiles from the dissipational merger models of H09 are shown as thick grey lines (labels as per Table 3.4).

3.5.1 NGC 1407

This galaxy is the only galaxy in our sample for which we have previous literature gradient values available to compare our results to. Unfortunately, it is not our best dataset in that the radial coverage is limited. Nevertheless, as seen in Figure 3.7, the general agreement of our CaT$_{F09}$ measured metallicities with the metallicities measured from long-slit observations by Spolaor et al. (2008b) is reasonable. Although the individual values agree with the Spolaor et al. (2008b) data within the uncertainties at similar galactocentric radii, the rolling average shows a slight offset in metallicity ($\sim 0.3$ dex). The Spolaor et al. (2008b) data were obtained...
3.5. Results

from optical spectra and calculated using the well tested $\chi^2$ fitting method of Lick indices of Proctor and Sansom (2002). Considering that the present study may be sampling different stellar populations since 1) we sample a broader range of position angles, and 2) our wavelength range is much redder than Spolaor et al. (2008b), this broad agreement is an indication that the metallicities measured from the $CaT_{F09}$ are reliable. Moreover, while we estimate that uncertainties due to the lack of flux calibration of our spectra are negligible compared to the quoted uncertainties, we cannot completely rule out the possibility that systematic offsets could be present.

Both the $CaT_{F09}$ and derived metallicities reveal a steep gradient falling to $[Fe/H] \sim -1.7$ dex at a radius of $\sim 100$ arcsec. Although the radial range covered here is limited, the $CaT_{F09}$ and metallicity gradients show no clear sign of levelling off.

3.5.2 NGC 2768

As can be seen in Figure 3.8 the data for NGC 2768 cover a more extensive radial range than our NGC 1407 data. They also contain more individual measurements than for any other galaxy in our sample and exhibit smaller scatter. The central metallicity value measured by Howell (2005) is consistent with our innermost data points. A visual inspection of Figure 3.8 reveals a steep average metallicity gradient in the inner parts that steepens slightly before becoming shallower at a radius of $\sim 80$ arcsec around a metallicity of $[Fe/H] = -1.0$ dex.

Although not inconsistent (i.e., still within the quoted uncertainties), a few outer slits seem to exhibit $CaT_{F09}$ values beyond the upper limit permitted by Vazdekis et al. (2003) (see Figure 3.8). Because of the uncertainties related to model extrapolation and especially given the steepness of the predicted relationship between $CaT_{F09}$ and $[Fe/H]$ at high $CaT_{F09}$ values, we consider these metallicity data unreliable.

3.5.3 NGC 4494

Because shorter exposure times were used for NGC 4494, the number and spatial coverage of our measurements are much smaller than for the previous two galaxies. Despite the large scatter in our measured metallicity values, the agreement with the
Chapter 3. Metallicity Gradients at Large Galactocentric Radii Using the Near-infrared Calcium Triplet

Figure 3.8: CaT\textsubscript{F09} (top panel) and metallicity (lower panel) gradients for NGC 2768. The star shows the central \((r \leq r_e/8)\) metallicity as measured by Howell (2005) and the circles represent our data. Hollow circles and upper arrow uncertainties are used when the CaT\textsubscript{F09} is beyond the upper limit (thin dashed lines) of the V03 SSP models. Thick solid lines are rolling averages. Profiles from the dissipational merger models of H09 are shown as thick grey lines (labels as per Table 3.4).

The central estimate from Denicol\'{o} et al. (2005) is good. Interestingly, the data show no visible gradient in the raw CaT\textsubscript{F09} measurements (see Figure 3.9) and the CaT\textsubscript{F09} values seem to scatter about the upper limit of the V03 models. Unfortunately, the majority of the measured metallicity points in NGC 4494 are very high (i.e., consistent with \([Fe/H] \gtrsim 0.2\) dex) within the galactocentric radius probed and an accurate metallicity gradient could not be measured. For this reason, we cannot comment on the presence or absence of a metallicity gradient in this galaxy based on the current dataset.

It is clear that longer exposure times and more data are required to properly constrain the metallicity gradient in this galaxy at large galactocentric radii. Moreover, as for NGC 2768, the large CaT\textsubscript{F09} values found indicate that the method presented herein may not be accurate at metallicities near solar and particularly beyond \([Fe/H] = +0.2\) dex. Luckily, the negative radial metallicity gradients present in most galaxies mean that usually metallicities at large radii are sub-solar.
3.5. Results

Figure 3.9: \( CaT_{\text{F09}} \) (top panel) and metallicity (lower panel) gradients for NGC 4494. The star shows the central \( r \leq r_e/8 \) metallicity as measured by Denicoló et al. (2005) and the circles represent our data. Hollow circles and upper arrow uncertainties are used when the \( CaT_{\text{F09}} \) is beyond the upper limit (thin dashed lines) of the V03 SSP models. Thick solid lines are rolling averages. We do not measure a significant \( CaT_{\text{F09}} \) or \([Fe/H]\) gradient for this galaxy. Profiles from the dissipational merger models of H09 are shown as thick grey lines (labels as per Table 3.4).
### Chapter 3. Metallicity Gradients at Large Galactocentric Radii Using the Near-infrared Calcium Triplet

#### Table 3.4: Relevant properties of H09 dissipative major merger simulations (column 1) selected based on their matching of the luminosity profiles of our sample galaxies (column 2). The quoted stellar mass (column 3) is that of the remnant. Central velocity dispersions (column 4) are median line-of-sight values measured within 1 \( r_e \) (as per column 5). \( f_{\text{gas}} \) (column 6) is the mass fraction of the merging disks in the form of cold gas just before the final merger.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Galaxy</th>
<th>Stellar mass ((10^{11} M_\odot))</th>
<th>(\sigma_0) ((\text{km s}^{-1}))</th>
<th>(r_e) ((\text{kpc}))</th>
<th>(f_{\text{gas}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>d3e2</td>
<td>NGC 2768</td>
<td>1.00</td>
<td>158.9</td>
<td>4.02</td>
<td>0.18</td>
</tr>
<tr>
<td>d4e2</td>
<td>NGC 1407</td>
<td>2.51</td>
<td>231.2</td>
<td>5.26</td>
<td>0.20</td>
</tr>
<tr>
<td>d4f</td>
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<td>202.9</td>
<td>5.44</td>
<td>0.23</td>
</tr>
<tr>
<td>d4h2</td>
<td>NGC 2768</td>
<td>1.00</td>
<td>161.4</td>
<td>3.73</td>
<td>0.19</td>
</tr>
<tr>
<td>d4k</td>
<td>NGC 1407</td>
<td>2.51</td>
<td>226.1</td>
<td>4.93</td>
<td>0.23</td>
</tr>
<tr>
<td>e3e</td>
<td>NGC 4494</td>
<td>1.00</td>
<td>154.0</td>
<td>5.02</td>
<td>0.09</td>
</tr>
<tr>
<td>e3k</td>
<td>NGC 4494</td>
<td>1.00</td>
<td>154.9</td>
<td>5.03</td>
<td>0.11</td>
</tr>
<tr>
<td>e4k</td>
<td>NGC 1407</td>
<td>2.51</td>
<td>202.1</td>
<td>7.34</td>
<td>0.10</td>
</tr>
<tr>
<td>vc3ve3y_j</td>
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<td>1.00</td>
<td>154.0</td>
<td>4.46</td>
<td>0.14</td>
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<td>145.1</td>
<td>5.90</td>
<td>0.03</td>
</tr>
<tr>
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<td>139.4</td>
<td>6.14</td>
<td>0.03</td>
</tr>
<tr>
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<td>5.86</td>
<td>0.04</td>
</tr>
</tbody>
</table>

In this pilot study, we develop a new technique to measure metallicity gradients at large galactocentric radii by expanding on the technique presented in P09. Using the CaT and the SSP models of V03, we obtain spectroscopic metallicity measurements out to 1.4\( r_e \), 1.9\( r_e \) and 1.5\( r_e \) for NGC 1407, NGC 2768 and NGC 4494, respectively. We find that the metallicity gradients are not well described as a straight line in log-log space as their slope varies with galactocentric radius. The slope variations themselves contain information about the processes involved in the galaxy’s formation.

In order to better understand our observed metallicity gradients and the processes involved in their formation, we compare our results to the predictions from the models of H09. In H09, suites of hydrodynamic simulations of dissipational disk-disk galaxy merger remnants are compared to the observed properties (sizes and surface brightness profiles) of individual E galaxies. The simulations determine the enrichment (i.e. metallicity) self-consistently from star formation and include a prescription for AGN and supernova feedback. For the individual galaxies in our sample, the models producing a remnant whose simulated surface brightness profile yield the best \( \chi^2 \) matches to a given galaxy’s observed surface brightness profile are selected (see Table 3.4) with no prior on the metallicity or mass. Thus the predicted...
3.6. Discussion

H09 metallicity gradients are not scaled to match the observed data. In Figure 3.7, 3.8 and 3.9 we show the line-of-sight averaged and $B$-band luminosity-weighted stellar metallicity profiles predicted 3 Gyr after the merger of these selected models for NGC 1407, NGC 2768 and NGC 4494, respectively. The simulated metallicity profiles are not strongly sensitive to the chosen line-of-sight or age of the merger.

Although the model metallicities are determined self-consistently from stars formed in the merger simulations, progenitor disks at the start of the simulation must have some ‘initial’ metallicity. The chosen initial metallicities of the progenitors will not change the central predicted metallicity of the remnant significantly as it is dominated by the merger induced dissipational star formation. However, the initial metallicity of the progenitors will come to dominate the metallicity of the remnant at sufficiently large radii. This sets an effective metallicity ‘floor’ at large radii.

First we compare our results with the simulated systems from H09 where the progenitor disks are initialised to lie on the observed redshift $z = 0$ mass-metallicity relation (e.g., Tremonti et al., 2004) with a uniform metallicity at all radii. We find that this predicts too high a metallicity at large radii in the remnants to be compared with the current dataset. In the simulations shown in Figure 3.7, 3.8 and 3.9, we lower the metallicity of the progenitors by a factor of $\sim 3$ (i.e., $\sim -0.48$ dex). Again the metallicities at $\leq 1r_e$ are unchanged, but those at large radii are reduced. Under the dissipational major-merger formation paradigm, this lowered ‘floor’ suggests that 1) the remnant’s metallicity increasingly reflects that of its progenitors’ stars as the radius probed increases; and 2) since the galaxies in question have relatively early formation times ($z \geq 1$ to 2), the appropriate ‘initial’ mass-metallicity relation is not that observed today (i.e., $z = 0$) but that at these redshifts, which yields lower metallicities (e.g., Erb et al., 2006, Lara-López et al., 2009).

From the H09 simulations, we find that the central luminosity profile of NGC 1407 is well matched by mergers of intermediate gas-richness with gas fractions ($f_{\text{gas}}$) at the time of merger $\sim 10\%$, typical of $L^*$ galaxies. The theoretical expectation is a relatively smooth metallicity profile, similar to that observed for radii $\lesssim 50$ arcsec. Once again, the different profiles shown correspond to the three simulations that provide the best match to the observed surface brightness profile with no prior on the metallicity or mass of NGC 1407. Thus, the amount of dissipation needed to
match the luminosity profile appears to also provide a good match to the metallicity gradients for radii \( \lesssim 50 \) arcsec. Beyond that radius however there is an observed steepening of the metallicity gradient, which is not predicted by the models. This could be an indication that either 1) the initial metallicity of the progenitors is still too high (i.e., the ‘floor’ should be set lower initially); or 2) that a dissipative major merger remnant is not a good description of the formation and evolution of NGC 1407. Under both the early dissipative collapse scenario and dissipative merger scenarios, an early formation and assembly is required. Indeed, as concluded by Spolaor et al. (2008b), NGC 1407’s steep metallicity gradient, uniform old age and smooth photometric profile are consistent with a formation in which early dissipation played a major role. Moreover, it is not clear that a disk-disk major merger with plausible progenitors at moderate redshift could reproduce such a gradient unless the progenitors themselves possessed strong metallicity gradients (see Di Matteo et al., 2009). Alternatively, and still consistent with a hierarchical merging scenario, it is possible that the outskirts of NGC 1407 were built up primarily from smaller shredded systems (i.e., multiple minor-mergers, see Naab et al. 2009), which typically have lower metallicities.

The matching of the observed and simulated photometric profiles of H09 is more ambiguous for NGC 2768 because it contains a lot of dust and exhibits several fine structures such as filaments and a ring of ionized gas (Martel et al., 2004; Lauer et al., 2005). This causes ambiguity with respect to selecting the best fitting models. Indeed, H09 find reasonable matches with both relatively gas-poor mergers \((f_{\text{gas}} \sim 3 – 5 \) per cent\) to relatively gas-rich \((f_{\text{gas}} \sim 20 – 30 \) per cent\) ones. Unfortunately, the metallicity profiles are not sufficiently accurate to break this degeneracy. Nevertheless, the rolling average suggests that the simulations of H09 are a reasonable match to the measured metallicity profile and particularly for the relatively gas-rich models (i.e., \(f_{\text{gas}} \sim 20 – 30 \) per cent).

Unfortunately, the metallicity gradient for NGC 4494 is not well constrained by our data. The shorter exposure time has yielded fewer data points to constrain the gradient. Moreover, at large \(CaT_{\text{F09}}\) (and velocity dispersions), the inferred metallicities are more uncertain and may yield unreliable results especially in modest signal-to-noise data. For this reason, we could not detect and measure a reliable metallicity gradient in NGC 4494. On the other hand, our data suggest that the
3.7 Summary

In this Chapter, we have described a new technique for obtaining radial metallicity gradients of galaxies out to large galactocentric radii using the DEIMOS multi-object spectrograph on the Keck telescope. We use the NIR CaT spectral feature and convert our $CaT_{F09}$ index into metallicity with the use of the V03 SSP models. This new technique is then applied to three intermediate mass to massive ETGs as a pilot study. Our results agree well with previous literature inner values. We find that at large galactocentric radii our measured metallicity gradients are not well described with straight lines (in log-log space) and show significant variations with galactocentric radius. A comparison to theoretical models is used in order to interpret our metallicity gradients.

We conclude that NGC 1407 is likely to have formed the bulk of its stars via dissipational processes. This is consistent with the early dissipative collapse scenario. However, we also hypothesise that the low metallicity stellar populations probed in the outskirts of NGC 1407 could have been hierarchically assembled from smaller low-metallicity systems. For NGC 2768, the measured metallicity profile is well reproduced by the dissipative major merger models of H09. We were unable to measure the metallicity gradient in NGC 4494 due to both the lower quality of this dataset and the fact that the measured $CaT_{F09}$ values scatter around the upper limit permitted by the models. Nevertheless, we are able to conclude that the metallicity of NGC 4494 as measured via the $CaT_{F09}$ is $[Fe/H] \gtrsim 0.2$ dex within the galactocentric radii probed. We study this galaxy in further detail in the following Chapter using added data. The limitations of our new technique as a function of signal-to-noise, metallicity and velocity dispersion are also discussed.
Global Properties of ‘Ordinary’ Early-type Galaxies: photometry and spectroscopy of stars and globular clusters in NGC 4494

4.1 Introduction

This Chapter brings together the spectroscopic techniques described in Chapter 2 and Chapter 3, as well as wide-field imaging, to obtain spatially resolved light and colour profiles, kinematics and abundances of the stars and GCs in and around NGC 4494. This galaxy is often described as an “ordinary elliptical” galaxy (e.g., Capaccioli et al., 1992; Lackner and Ostriker, 2010) mainly based on its typical light profile.

While the most massive nearby E galaxies are in principle easier to study, their formation may have been atypical due to their often special location at the centre of large potential wells such as galaxy groups or clusters. Therefore, in order to understand the formation of the average galaxy, it is necessary to avoid “special” environments and aim for more typical galaxy masses (i.e., around the turnover of the galaxy stellar mass function $M^* = 10^{11} M_\odot$). It is for these reasons that we have chosen to focus this Chapter on NGC 4494. Indeed, its intermediate density environment is another aspect that makes NGC 4494 fairly ordinary, or average as it has been described in the literature as either isolated (Lackner and Ostriker, 2010) or loose group member (Forbes et al., 1996; Larsen et al., 2001) because it is located
at the edge of the Coma I cloud. It is neither a large nor a small galaxy with a
stellar mass of $\sim 10^{11} \, M_\odot$ (see Table 4.1). Its E morphology is also typical as ETGs
may contain over 50 per cent of the total stellar mass in the local Universe (Bell
et al., 2003; Baldry et al., 2004). It contains an inner dust ring ($r < 4$ arcsec, Lauer
et al., 2005), is quite round with an axis ratio of $q = 0.87$ (see Table 4.1) and shows a
very smooth luminosity profile with a central cusp (Lauer et al., 2007). Peculiarities
include a kinematically decoupled core (Bender et al., 1994) or double maxima
(Krajnovic et al., 2011) in the inner $\sim 19$ arcsec, beyond which sustained rotation
($V_{\text{rot}} \sim 60 \, \text{km s}^{-1}$) is observed out to $\sim 3r_e$ with a possible “pinching” or “flattening”
of the kinematics starting at $\sim 1.5r_e$ (P09). Other notable properties are a two order
of magnitudes deficiency in X-ray luminosity for its optical luminosity (O’Sullivan
and Ponman, 2004) and a possible deficiency in dark matter (Romanowsky et al.,
2003; Napolitano et al., 2009, hereafter N09).

Our approach is to study NGC 4494 in great detail to constrain the formation
of “ordinary” elliptical galaxies. To this end we study its structure, kinematics and
stellar populations, as well as its GCs, using imaging and spectroscopy. We also
include literature data. Our study is unique and one of the most complete studies
of an individual “ordinary” elliptical galaxy and its GC system to date. We present
arguably the first large catalogue of GC recession velocities in an ordinary ETG.

Apart from the test of galaxy formation described above, several other scientific
problems are tackled with this extensive dataset. For example, the assumption that
field stars, planetary nebulae and metal-rich GCs are all tracing the same population
is tested by cross-checking their properties for consistency. Moreover, the well-known
GC dichotomy usually probed in colour (or metallicity) space is probed in kinematic
space.

This Chapter is divided as follows: Section 4.2 presents the photometric and
spectroscopic data. The surface brightness/density profile, kinematics, colours and
metallicity distribution of the stars and GCs are found in Section 4.3. These results
and their implication for the key science questions described above are discussed in
Section 4.4 Finally, we give a brief summary and our conclusions in Section 4.5.
### Table 4.1: Properties of nine massive ETGs with significant GC kinematic samples from the literature.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Hubble Type</th>
<th>$P_{A_{\text{phot}}}$ (deg)</th>
<th>$q_{\text{phot}}$ (K band)</th>
<th>Distance (Mpc)</th>
<th>$r_e$ (arcsec)</th>
<th>$M_B$ (mag)</th>
<th>$M_K$ (mag)</th>
<th>Stellar mass ($10^{11} M_\odot$)</th>
<th>$V_{\text{sys}}$ (km s$^{-1}$)</th>
<th>$\sigma_0$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M49 E2</td>
<td>163</td>
<td>0.81</td>
<td>15.1 ± 0.7</td>
<td>104</td>
<td>-21.5 ± 0.16</td>
<td>-25.5 ± 0.1</td>
<td>3.1 ± 0.3</td>
<td>997 ± 7</td>
<td>294 ± 3</td>
<td></td>
</tr>
<tr>
<td>M60 E2</td>
<td>108</td>
<td>0.81</td>
<td>16 ± 1</td>
<td>69</td>
<td>-21.2 ± 0.2</td>
<td>-25.2 ± 0.2</td>
<td>2.4 ± 0.4</td>
<td>1117 ± 6</td>
<td>335 ± 4</td>
<td></td>
</tr>
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<td>152</td>
<td>0.86</td>
<td>15 ± 1</td>
<td>95</td>
<td>-21.3 ± 0.1</td>
<td>-25.1 ± 0.1</td>
<td>2.2 ± 0.2</td>
<td>1307 ± 7</td>
<td>335 ± 5</td>
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<td>NGC 1399</td>
<td>E1</td>
<td>150</td>
<td>1.00</td>
<td>80</td>
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<td>-25.0 ± 0.2</td>
<td>2.0 ± 0.4</td>
<td>1425 ± 4</td>
<td>342 ± 6</td>
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</tr>
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<td>60</td>
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<td>-21.4 ± 0.3</td>
<td>-25.4 ± 0.3</td>
<td>3.0 ± 0.9</td>
<td>1779 ± 9</td>
<td>272 ± 6</td>
<td></td>
</tr>
<tr>
<td>NGC 3379</td>
<td>E1</td>
<td>68</td>
<td>9.8 ± 0.5</td>
<td>35</td>
<td>-19.7 ± 0.1</td>
<td>-23.7 ± 0.1</td>
<td>0.59 ± 0.06</td>
<td>911 ± 2</td>
<td>209 ± 2</td>
<td></td>
</tr>
<tr>
<td>NGC 4494</td>
<td>E1-2</td>
<td>173</td>
<td>15.8 ± 0.9</td>
<td>49</td>
<td>-20.4 ± 0.2</td>
<td>-24.2 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>1344 ± 11</td>
<td>150 ± 4</td>
<td></td>
</tr>
<tr>
<td>NGC 4636</td>
<td>E0-1</td>
<td>143</td>
<td>13.6 ± 0.9</td>
<td>89</td>
<td>-20.2 ± 0.2</td>
<td>-24.2 ± 0.1</td>
<td>0.95 ± 0.08</td>
<td>938 ± 4</td>
<td>203 ± 4</td>
<td></td>
</tr>
<tr>
<td>NGC 5128</td>
<td>S0</td>
<td>43</td>
<td>0.89</td>
<td>305</td>
<td>-20.2 ± 0.2</td>
<td>-24.0 ± 0.1</td>
<td>0.78 ± 0.07</td>
<td>547 ± 5</td>
<td>120 ± 7</td>
<td></td>
</tr>
</tbody>
</table>

Hubble types (column 2) are as per NASA/IPAC Extragalactic Database (NED). Position angles and axis ratios (columns 3, 4) are from 2MASS. Distances (column 5) are based on surface brightness fluctuations (Tonry et al., 2001) and include the distance moduli correction of Jensen et al. (2003). Effective radii (column 6) are taken from the Third Reference Catalogue of Bright Galaxies (RC3, de Vaucouleurs et al., 1991) for all galaxies except NGC 5128, which is from Dufour et al. (1979). $B$- and $K$-band absolute magnitudes (columns 7, 8) are calculated from RC3 and 2MASS apparent magnitudes, respectively, and using the distances quoted in column 5. Stellar masses (column 9) are calculated from the $K$-band magnitude of column 8 assuming a $M/L_K = 0.959$ ratio corresponding to the VDSS SSP of age 10 Gyrs and solar metallicity. Systemic velocities (column 10) are from NED. Central velocity dispersions (column 11) are as per Paturel et al. (2003).
Figure 4.1: DSS image of NGC 4494 showing the positions of our science spectra. Circles and squares represent kinematically confirmed GCs and UCDs, respectively, while crosses show the position of galaxy light spectra. Green and black small symbols are used when the spectrum returned both CaT and kinematic information, while red symbols are used if only kinematic information could be extracted. Large black ellipses represent 3, 6 and 9 $r_e$ with the galaxy’s global photometric position angle and axis ratio. The HST field-of-view is shown in white.
4.2 Data

4.2.1 Imaging acquisition and reduction

Subaru Suprime-Cam (Miyazaki et al., 2002) imaging of NGC 4494 is analysed to understand the GC system and light profiles of NGC 4494. We obtained a $g$-band observation of NGC 4494 during a Gemini time exchange program (GN-2008A-C-12) on the night of 2008 April 2. Two additional bands ($r$ and $i$-bands) were acquired on a later date, 2010 April 4, through Keck time exchange. The total exposure times are 805, 365, and 540 seconds in the $g$, $r$ and $i$-bands, respectively. The seeing conditions in the respective bands are: 0.63, 0.56, and 0.58 arcsecs. Suprime-Cam data are prepared for analysis using standard imaging reduction techniques and a modified version of the sdfred data pipeline (Yagi et al., 2002; Ouchi et al., 2004). The Suprime-Cam field of view covers a $\sim 36 \times 29$ arcmin region centered on NGC 4494.

Suprime-Cam photometry is calibrated to the Sloan Digital Sky Survey DR7 (Abazajian et al., 2009) photometric system using point sources with $19 \leq i \leq 21.5$ magnitudes. The estimated $g$-, $r$- and $i$-band systematic uncertainty due to this calibration is 0.004, 0.005 and 0.004 mags, respectively. All photometry is Galactic extinction-corrected according to Schlegel et al. (1998).

The images are prepared for GC analysis by first modelling with IRAF/Ellipse and subtracting the galaxy light profiles. Ellipse is set to allow the center, position angle and ellipticity to vary. A bright blue star is $\sim 6$ arcmin away from NGC 4494 to the NNE. The scattered light from this star extends to a radius of $\sim 3.5$ arcmin, thus IRAF/Ellipse is also used to model and subtract its light in the $g$, $r$ and $i$-bands. Because the star and galaxy profiles overlap significantly, Ellipse is performed and subtracted iteratively on the light profiles 3 times. The final image products show a constant background value across the field.

A catalogue of GC candidates is constructed from the 3 Suprime-Cam mosaics. At the distance of NGC 4494, GCs are unresolved and appear as point-sources on the images. IRAF/DAOPHOT/FIND is used to locate objects on the field deviating by $3.8\sigma$ from a global background level. The difference between two different aperture magnitudes (2.5 and 5 pixels radii) is used as a way to identify and remove extended
sources from the GC catalogue (see e.g. Spitler et al., 2008b) using an upper cutoff of $\sim 0.5 \pm 0.1$ mag depending on the filter. This is done for detected objects in each image. In principle and given the good seeing on the Subaru images, this step may exclude some interesting partially resolved large GCs or UCDs, however their study is beyond the scope of this Thesis and visual inspection of rejected objects shows that they are clearly extended galaxy-like objects. Aperture corrections are applied to the point sources and the photometric zeropoints derived from the above procedure are used. The three separate photometry catalogues are combined using a matching threshold of 1 arcsec.

To supplement the Suprime-Cam catalogue, an existing Hubble Space Telescope (HST) Wide-field Planetary Camera 2 (WFPC2) GC catalogue is incorporated into the GC analysis. The WFPC2 catalogue is provided by S. Larsen and is described in Larsen et al. (2001). See Section 4.3.2 for details on our selection of GC candidates.

### 4.2.2 Spectroscopy acquisition and reduction

Spectra were obtained as part of the SMEAGOL survey on two separate dark nights: 2008 April 8 (hereafter Night 1) and 2009 March 23 (hereafter Night 2) using DEIMOS. Three slit-masks were observed during Night 1 under good seeing conditions (FWHM $\sim 0.7$ arcsec) and 2 slit-masks were observed during Night 2, this time under variable seeing conditions ($0.8 \lessapprox \text{FWHM} \lessapprox 1.3$ arcsec). The galaxy light data for Night 1 only were presented in both P09 and Chapter 3. In addition to the data used in P09 and Chapter 3, the final dataset used here includes roughly twice as many galaxy light spectra and the whole set of GC spectra. The 1200 l mm$^{-1}$ grating centered on 7800 Å was used together with 1 arcsec slit width. This setup yields a resolution of $\Delta \lambda \sim 1.5$ Å (FWHM) and allows for the coverage of the CaT spectral region ($\sim$8400-8900 Å). A total of 3 and 4 half-hour exposures were taken yielding a total exposure time of 1.5 and 2 hours per mask for Night 1 and 2, respectively. Fig. 4.1 shows the positions of the slits that returned useful science spectra.

The DEIMOS data are reduced using the IDL SPEC2D data reduction pipeline provided online. An overview of the pipeline reduction procedure can be found in

1http://sages.ucolick.org/surveys.html
4.3 Analysis and results

In this section we describe how we extract the photometric, kinematic and stellar population information for both the galaxy light and the GC system. We also give an overview of the method used to fit the kinematics of NGC 4494. These results are interpreted and discussed in Section 4.4.

Figure 4.2: Example GC spectra (black) and fitted rPXF templates (red) for a bright (top panel), typical (middle panel) and faint (lower panel) GC in our sample. Shaded wavelength bands are regions affected by significant skyline residuals. GC apparent *i* magnitudes are given.

Section 2.2.2 The pipeline outputs the GC spectra with their corresponding fully propagated variance arrays as well as the subtracted background or ‘sky’ spectra for each slit. Fig. 4.2 shows example GC spectra for a range of signal-to-noise ratios.

We use the SKiMS technique described in P09 and Chapter 3 to extract the galaxy light spectra from these background spectra. Fig. 4.3 shows example galaxy light spectra for a range of signal-to-noise ratios.

4.3 Analysis and results

In this section we describe how we extract the photometric, kinematic and stellar population information for both the galaxy light and the GC system. We also give an overview of the method used to fit the kinematics of NGC 4494. These results are interpreted and discussed in Section 4.4.
Figure 4.3: Example galaxy light spectra (black) and fitted pPXF templates (red) for a high (top panel), typical (middle panel) and low (lower panel) signal-to-noise spectrum. Shaded wavelength bands are regions affected by significant skyline residuals. Galaxy $i$-band surface brightness ($\mu_i$) is given.
4.3. Analysis and results

Table 4.2: Results of Sérsic fits to the the galaxy surface brightness profile as a function of geometric radius (Eq. 4.1 fitted for $\mu_e$, $r_e$ and $n$) for points with $r > 5$ arcsec. Sérsic fits to the GC density profiles (Eq. 4.8 fitted for $N_e$, $R_e$, $n$ and $bg$) are also listed.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\mu_e$</th>
<th>$N_e$</th>
<th>$r_e$</th>
<th>$R_e$</th>
<th>$n$</th>
<th>$bg$</th>
</tr>
</thead>
<tbody>
<tr>
<td>galaxy g</td>
<td>22.81 ± 0.03</td>
<td>54.6 ± 0.8</td>
<td>3.72 ± 0.09</td>
<td>—</td>
<td></td>
<td></td>
</tr>
<tr>
<td>galaxy r</td>
<td>21.90 ± 0.03</td>
<td>53.0 ± 0.6</td>
<td>3.52 ± 0.09</td>
<td>—</td>
<td></td>
<td></td>
</tr>
<tr>
<td>galaxy i</td>
<td>21.51 ± 0.02</td>
<td>48.2 ± 0.5</td>
<td>3.47 ± 0.06</td>
<td>—</td>
<td></td>
<td></td>
</tr>
<tr>
<td>all GCs</td>
<td>5 ± 1</td>
<td>100 ± 10</td>
<td>1.7 ± 0.5</td>
<td>0.28 ± 0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>blue GCs</td>
<td>2.2 ± 0.8</td>
<td>138 ± 24</td>
<td>1.8 ± 0.7</td>
<td>0.22 ± 0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>red GCs</td>
<td>3.1 ± 0.4</td>
<td>83 ± 6</td>
<td>0.8 ± 0.2</td>
<td>0.053 ± 0.005</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3.1 Galaxy light

Stellar light profile

We first quantify the stellar light distribution of NGC 4494. Figure 4.3 shows the surface brightness profile extracted as described in Section 4.2.1 in the $g$- and $i$-bands together with literature values. We fit Sérsic profiles (Sérsic, 1963) to the surface brightness profile ($\mu(r)$) with geometric radius $r > 5$ arcsec to avoid the inner disk as per N09. In practice, we fit:

$$\mu(r) = \mu_e + 2.5b_n \ln(10) \left( (r/r_e)^{1/n} - 1 \right)$$  \hspace{1cm} (4.1)

where $b_n = 1.9992n - 0.3271$ (i.e. eq. 6 of Graham and Driver, 2005) for the Sérsic index ($n$), $r_e$ and the surface brightness at $1r_e$ ($\mu_e$). The resulting fits are shown in Fig. 4.3 and Table 4.2. We measure values between $48 \leq r_e \leq 55$ arcsec depending on the photometric filter used. Throughout this work we use the literature value of $r_e = 49$ arcsec $\approx 3.76$ kpc (Table 4.1) as it lies within the range of our measured values and is thus a good compromise.

Stellar kinematics

The stellar kinematics of NGC 4494 have been probed out to large radii in P09 using the SKiMS method. Here our galaxy spectral sample is roughly twice that of P09. We measure the velocity moments (recession velocity, velocity dispersion
and Gauss-Hermite coefficients $h_3$ and $h_4$) for all the galaxy light spectra using the \texttt{pPXF} routine described in Cappellari and Emsellem (2004). The \texttt{pPXF} routine uses a set of 13 stellar templates to determine the best overall kinematic parameters and weighted combination of templates that minimises the residuals between the spectrum and the final resulting fit (see Cappellari and Emsellem, 2004, for more details). The stellar templates are described in Section 2.2.2. The fitted spectral range is limited to 8450–8750 Å for stability and regions heavily contaminated by skylines are not fitted (see Fig. 4.3). Each fit is carefully inspected for quality control. Uncertainties on the measured velocity moments are estimated using Monte Carlo methods. For each spectrum, we randomly reshuffle the residuals between the best fit template and the original spectra in the wavelength region fitted by \texttt{pPXF} before re-fitting. This is repeated 100 times for each individual spectrum. We use the standard deviation on the velocity moments for the 100 Monte Carlo realisations as our estimate of the random uncertainty.

Fig. 4.5 shows the velocity moments as a function of position angle (PA) for our sample of spectra. Individual values are tabulated in Foster et al. (2011). The
Figure 4.5: Variation in $CaT_{F09}$ and velocity moments of the galaxy light as a function of PA for spectra with $r \leq r_e$ (black), $1r_e < r \leq 2r_e$ (red), and $r > 2r_e$ (gray). Kinemetry fits are shown with solid lines for the observed recession velocity ($V_{obs}$) and velocity dispersion in each radial bin, as well as for $h_3$ for spectra within 1$r_e$. Dashed lines represent the $CaT_{F09}$ saturation level (top panel), systemic velocity (second panel) and $h_3 = 0$ (bottom panel). The photometric position angle is $PA_{phot} = 173$ degrees.
galaxy’s stars show clear major-axis rotation. The amplitude of the rotation is roughly constant all the way out to $> 2r_e$ and shows a flattening (i.e., axis ratio $q_{\text{kin}} = 0.42 \pm 0.06$ is low) at large radii ($r \gtrsim 2r_e$). The velocity dispersion decreases with radius. For the inner $h_3$ measurements, we find a clear trend with position angle although such a trend is not clearly visible beyond $1r_e$. The fourth velocity moment ($h_4$) has constant amplitude at all radii within the uncertainties.

In order to better understand the kinematic structure of NGC 4494, we use kinemetry to fit the model of an isotropic rotating ellipsoid (or inclined disk). Kinemetry is an analog to photometry where instead of fitting a model of the stellar light distribution, we fit a model of the kinematics (see e.g. Krajnović et al. 2006; P09). In what follows, we generalise and improve on the technique presented in P09 to obtain kinemetry fits to discrete and semi-discrete 2-dimensional data. P09 have shown that kinemetry using this model provides a good fit to the inner regions probed by SAURON (Emsellem et al., 2004). In contrast to P09 where the data were binned in circular annuli, here the data are binned in overlapping ‘radial’ (semi-major axis) intervals that, together with the position angle and axis ratio, define ‘elliptical annuli’. The $j^{th}$ annulus (or bin) contains a subset of $N_j$ observed recession velocity data points ($V_{\text{obs,}i}$). We initially assume that the kinematic position angle and axis ratio of the galaxy coincide with the photometric values. The position angle and axis ratio of the $j^{th}$ elliptical annulus are iteratively refined to match the kinematics as the algorithm fits for the kinematic position angle ($P A_{\text{kin},j}$), axis ratio ($q_{\text{kin},j}$) and the amplitude of the rotation ($V_{\text{rot},j}$) using $\chi^2$ minimisation.

In practice, we first define an inner elliptical annulus ($j = 1$) whose short semi-major axis length ($a_j$) is the distance to the closest data point and whose long semi-major axis length is $a_j + \Delta a_j$. We perform a $\chi^2$ minimisation of the data points contained within this elliptical annulus to the model. For the $j^{th}$ annulus, the $\chi^2$ is computed using the following equation:

$$
\chi^2_{V,j} = \sum_{i=1}^{i=N_j} \left( \frac{1}{(\Delta V_{\text{obs,}i})^2} (V_{\text{obs,}i} - V_{\text{mod,}i,j})^2 \right),
$$

where

$$
V_{\text{mod,}i,j} = V_{\text{sys}} \pm V_{\text{rot,}j} \sqrt{1 + \left( \frac{\tan(P A_{i} - P A_{\text{kin},j})}{q_{\text{kin},j}} \right)^2},
$$

and $V_{\text{mod,}i,j}$ is the predicted recession velocity at position angle $P A_{i}$ for the $j^{th}$ annulus. The symbol $\Delta V_{\text{obs,}i}$ represents the uncertainty associated with each data point.
4.3. Analysis and results

and the ambivalent sign is positive (negative) if \((PA_i - PA_{\text{kin},j})\) is in the first or fourth (second or third) quadrants. In Equations 4.2 and 4.3, \(PA_i\) and \(\Delta V'_{\text{obs},i}\) are the position angle and the uncertainty on the recession velocity measurement of the \(i\)th data point, respectively. The systemic velocity of NGC 4494 \((V_{\text{sys}} = 1338.5\text{ km s}^{-1})\) is measured by fitting the inner, highest signal-to-noise data only prior to fitting the full dataset.

For each iteration within the \(j\)th annulus, a new set of parameters \((V_{\text{rot},j}, PA_{\text{kin},j}, q_{\text{kin},j})\) is found and the values of \(PA_{\text{kin},j}\) and \(q_{\text{kin},j}\) are used to update the shape and orientation of the elliptical annulus to be used in the next iteration \((a_j\) and \(\Delta a_j\) remaining fixed). Therefore, by construction this changes the selected member data points in the \(j\)th bin slightly for each iteration. After 15 iterations, we move out to the next ‘radial’ bin (i.e. \((j + 1)\)) by increasing the length of the short semi-major axis such that \(a_{j+1} = a_j + (\Delta a)/3\). The factor of \(1/3\) used here is chosen to increase the number of radial sub-samples or bins in order to smoothly define the kinemetry radial profile. The semi-major axis bin width \((\Delta a_{j+1})\) increases as a function of \(a_{j+1}\) according to a de Vaucouleurs \((1953)\) surface brightness profile (i.e. \(\propto 1/(a_{j+1})^{1/4}\)) in order to compensate for the lower signal-to-noise ratio at large galactocentric distances. With this setup, there are 15 overlapping bins, each containing \(\sim 25\) data points. This process continues until the radial extent of the data is covered.

In order to obtain a \(\chi^2/dof \approx 1\) at all radii and particularly in the inner regions we add an uncertainty of \(5\text{ km s}^{-1}\) in quadrature to the Monte Carlo uncertainties (i.e., \(\Delta V'_{\text{obs},i} = \sqrt{(\Delta V_{\text{obs},i})^2 + (5\text{ km s}^{-1})^2}\)). While the relative amplitudes of the uncertainties are crucial in order to obtain stable fits, this monotonic increase of the estimated uncertainties has a negligible effect on our fitted values. Nevertheless, it is an indication that either (1) there are velocity substructures at small galactocentric radii such that the model of a simple rotating isotropic ellipsoid is not appropriate or (2) the uncertainties are slightly underestimated. Indeed, the latter is likely since our quoted random uncertainties are obtained using Monte Carlo methods on our spectra and not independent measurements. For example, due to the finite (non-zero) length of the slits on the mask, their position angle, the effects of seeing, etc, independent measurements of the kinematics for the same “position” around the galaxy using either another instrument, setup or mask could yield slightly different values. For this reason, there could reasonably be some unaccounted for systematics.
Figure 4.6: Results of our kinemetry fits (solid lines) as a function of the major axis equivalent radius ($1r_e = 49$ arcsec $\approx 3.76$ kpc) with 68% confidence intervals (hatched regions). Black, dark blue and red represent fits to the stellar light, the blue and red GCs, respectively. The top panel shows the value of the $\chi^2$ per degree-of-freedom for the fits of the first velocity moment only (i.e. $V_{rot}$). Light blue, green and orange filled symbols show results of [N09] and [Coccato et al. 2009] from long-slit spectra, planetary nebulae (PNe) and galaxy light photometry, respectively.
of order $\sim 5 \text{ km s}^{-1}$. Finally, two data points deviating from the best fit at the $> 3\sigma$ level were excluded.

The kinemetry fits for the higher order velocity moments (velocity dispersion and $h_3$) are done in parallel in each annulus and using the values of $PA_{\text{kin},j}$ and $q_{\text{kin},j}$ obtained from the recession velocity kinemetry fits. In principle the position angle and axis ratio of these higher order velocity moments need not be equal to those of the recession velocity, but our data do not constrain these two parameters properly. Indeed, the velocity dispersion data in Fig. 4.5 show a hint of a dip along the minor axis ($PA \sim 83$ and 263 degrees) for points beyond $\sim 1r_e$ (i.e., red and grey points), suggesting that the kinematic flattening (i.e., low $q_{\text{kin}}$) is present in the velocity dispersion also. While this dip is suggestive, we are unable to reliably fit the axis ratio of the velocity dispersion explicitly with the current dataset and assume that of the recession velocity moment.

In practice, for the $j^{th}$ bin we fit the velocity dispersion ($\sigma_j$) using $\chi^2$-minimization where

$$\chi^2_{\sigma,j} = \sum_{i=1}^{i=N_j} \left( \frac{\sigma_{\text{obs},i} - \sigma_j}{\Delta\sigma'_{\text{obs},i}} \right)^2, \quad (4.4)$$

Eq. 4.4 is different in form from Eq. 4.2 because the velocity dispersion is an even moment. In Eq. 4.4 $\sigma_{\text{obs},i}$ and $\Delta\sigma'_{\text{obs},i} = \sqrt{\Delta\sigma^2_{\text{obs},i} + (8 \text{ km s}^{-1})^2}$ are the measured recession velocity of the $i^{th}$ spectrum and its associated random uncertainty ($\Delta\sigma_{\text{obs},i}$) with an additional uncertainty of $8 \text{ km s}^{-1}$ added in quadrature in order to obtain a $\chi^2/dof \approx 1$ as for the fits to $V_{\text{obs}}$ above, respectively.

Similarly, we minimize

$$\chi^2_{H_3,j} = \sum_{i=1}^{i=N_j} \frac{1}{\Delta h_{3,\text{obs},i}^2} (h_{3,\text{obs},i} - h_{3,\text{mod},i,j})^2, \quad (4.5)$$

where

$$h_{3,\text{mod},i,j} = \pm \frac{H_{3,j}}{\sqrt{1 + \tan(PA_i-PA_{\text{kin},j})^2 q_{\text{kin},j}}}, \quad (4.6)$$

to obtain the amplitude of the variation in the third velocity moment ($H_3$). The symbols $h_{3,\text{obs},i}$ and $\Delta h_{3,\text{obs},i}$ corresponds to the measured $h_3$ value and its uncertainty for the $i^{th}$ data point, respectively.
Measurement uncertainties on individual velocity moments are propagated for the kinemetry fits using Monte Carlo methods. For each individual data point we have a measured uncertainty. Assuming that these uncertainties are Gaussian, we have a known distribution of possible measurements for each data point. Thus, for each point we randomly select from that distribution. Each time this is done for the entire dataset and we get a new set of possible measurements. The kinemetry algorithm described above is then applied to the new dataset. This exercise is repeated 100 times. From the resulting range of fits we determine the 68 per cent confidence interval of the best fit model allowed by the data.

We also use Monte Carlo methods to verify that kinemetry can be reliably applied to sparse data. We create a series of rotating ellipsoid models by varying the input rotational velocity $V_{\text{rot},\text{in}} = 50, 80$ and 100 km s$^{-1}$, and kinematic axis ratio $q_{\text{kin},\text{in}} = 0.5, 0.8$ and 1.0. For each model, we randomly sample 115 data points within $\sim 3r_e$ and assign measurement uncertainties consistent with our observed uncertainties at that radius. This is repeated 25 times for each of the $(V_{\text{rot},\text{in}}, q_{\text{kin},\text{in}})$ combinations. We verify how well the input parameters are then recovered using kinemetry. In general, we find that the standard deviation of the output rotational velocity varies between $\sigma_{V_{\text{rot},\text{out}}} = 5$ and 7 km s$^{-1}$, while $\sigma_{q_{\text{kin},\text{out}}} \sim 0.1$ for all $q_{\text{kin},\text{in}}$. We find that the fits are less stable when both $V_{\text{rot},\text{in}}$ and $q_{\text{kin},\text{in}}$ are low. In other words, the lower the rotation the harder it is to recover $V_{\text{rot},\text{in}}$ precisely as the uncertainties start to dominate over the low rotation signal. We do not find other “unexpected” systematics. We conclude that kinemetry can be applied to sparse data successfully provided that there is sufficient rotation to determine $V_{\text{rot}}$ reliably (i.e., the uncertainty does not dominate).

The results of the kinemetry fits to the data are shown in Fig. 4.6. In general, we find good agreement between the long-slit and planetary nebulae results of [N09] and Coccato et al. (2009) and our data from the SKiMS method. We have also tried fitting the PNe data from [N09] using our method for discrete velocities (see Section 4.3.2) and find good general agreement with Coccato et al. (2009) except around $2r_e \lesssim r \lesssim 3r_e$ where the fits did not converge due to an apparently low rotation. The trends described above and found by P09 are confirmed. We find sustained major-axis rotation at all radii consistent with both the results of [N09] and Coccato et al. (2009). We do not find evidence for minor-axis rotation. There
4.3. Analysis and results

is a slight decrease in velocity dispersion that levels off with radius at a value of \( \sim 100 \text{ km s}^{-1} \) beyond \( \sim 2.3 r_e \) slightly at odds with the velocity dispersion estimated from planetary nebulae but consistent with that of the GCs (see Section 4.3.2). The amplitude of the third velocity moment levels off beyond \( \sim 1.8 r_e \) at a value of \( H_3 \sim -0.03 \).

Emsellem et al. (2007) classified ETGs as slow- or fast-rotators according to a luminosity- and radius-weighted value of the angular momentum proxy \( \lambda_R = V_{\text{rot}}(r)/\sqrt{V_{\text{rot}}(r)^2 + \sigma(r)^2} \), where slow- and fast-rotators correspond to \( \lambda_R < 0.1 \) and 0.1, respectively. These classifications were made for radii \( \leq 1 r_e \), but P09 demonstrated that the picture could change dramatically with more radially extended data. In the case of NGC 4494, we find that a local \( \lambda_R \sim 0.35 \) (i.e. fast rotation) at virtually all probed radii, modulo a sharp dip around \( 0.1 r_e \) due to the kinematically decoupled core. In Emsellem et al. (2011), NGC 4494 is also found to be a fast-rotator using a new classification method that takes into account the ellipticity of the isophotes.

Although not as pronounced as originally found in P09, a slight kinematic twist is visible beyond \( \sim 2 r_e \) such that the kinematic position angle is different from the photometric position angle at large radii. We measure a radial change in the axis ratio such that the velocity distribution becomes flattened (i.e., small \( q_{\text{kin}} \)) as originally detected by P09. This behaviour is at odds with the measured isophotes that remain much rounder even at large radii with no sign of significant diskiness. We test the robustness of the flattening of \( q_{\text{kin}} \) at large radii using three methods. The first is the above described nominal method in which we allow \( q_{\text{kin},j} \) to freely vary and iteratively define the bins accordingly. Secondly, similarly to the binning method used in P09, we let the fitted \( q_{\text{kin},j} \) vary but fix the bin shapes to \( q_{\text{phot}} \), i.e. we do not let the kinematic axis ratio define the axis ratio of the bins. While this yields an overall larger \( \chi^2/dof \) value, lower values of \( q_{\text{kin},j} \) are still marginally preferred at large radii. Thirdly, we fix \( q_{\text{kin},j} = q_{\text{phot}} \) for both the binning and the fitting and for all bins \( (j) \). This yields substantially larger \( \chi^2/dof \) values than in the (first) nominal case. We conclude that the flattening of the kinematics is most robustly detected in the first method but is still marginally detected when the kinematic axis ratio is allowed to vary inside selection bins whose shape have fixed axis ratios. On the basis that the only self-consistent methods are the first and the third and
Figure 4.7: Relationship between the higher order Gauss-Hermite moments $h_3$ and $(V_{\text{obs}} - V_{\text{sys}})/\sigma$. Point sizes are proportional to the signal-to-noise ratio of the spectra. The anti-correlation between $h_3$ and $(V_{\text{obs}} - V_{\text{sys}})/\sigma$ suggests a disk structure is present. Typical uncertainties are shown in the upper left corner.

given that the third method yields significantly higher $\chi^2/dof$ values than the first, we conclude that the former is preferable. We also tried removing the apparent “outliers” located around $PA \sim 0$ and 360 degrees with recession velocities below 1570 km s$^{-1}$ to see if they were causing the flattening and the results did not change significantly. We conclude that the kinematic flattening is robust (i.e., $q_{\text{kin}}$ is indeed low).

Fig. 4.7 shows the relationship between measured $h_3$ and $(V_{\text{obs}} - V_{\text{sys}})/\sigma$, which is a measure of the fraction of rotational over pressure support. The anti-correlation between $h_3$ and $(V_{\text{obs}} - V_{\text{sys}})/\sigma$ is indicative of a disk kinematic structure. This may be the source of the flattened kinematics.

**Stellar colours and metallicities**

We investigate the radial colour gradient of the stars in NGC 4494. By doing this, we obtain a rough estimate of the radial metallicity gradient by assuming a fixed old GC-like age at all radii. In other words, we attribute any colour variation to changes in the metallicity (i.e. ignoring age effects). We convert $(g-i)_0$ colours into approximate metallicity using the empirical linear relationship derived by Sinnott
et al. (2010) for GCs in NGC 5128. This is shown in Fig. 4.8. The galaxy stellar light is generally red and shows an overall colour/metallicity gradient. Because all the visible dust is contained within the inner 4 arcsec (Lauer et al., 2005), we will assume that dust is not affecting our inferences on the metallicity at the radii probed here. Therefore, between 10 and 70 arcsec (or \(0.2r_e < r < 1.4r_e\)), the colour profile suggests a moderate metallicity variation with radius of \(-0.17 \pm 0.02\) dex per dex. Assuming a younger age would increase the colour-inferred metallicity. This metallicity gradient is somewhat low according to the relationship found by Spolaor et al. (2009) using spectroscopically metallicities, but fits comfortably within the range of metallicity gradients measured by Koleva et al. (2011) for galaxies of similar central velocity dispersions (i.e., \(\sigma_0 = 150 \text{ km s}^{-1}\)).

We use the CaT as a spectroscopic proxy of metallicity. We compute the CaT index value for each galaxy spectrum using the index definition and method from Chapter 3 (i.e. \(\text{CaT}_{F09}\)). The \(\text{CaT}_{F09}\) is corrected for velocity dispersion broadening and converted into \([\text{Fe/H}]\) using the single stellar population (SSP) models of V03 following Chapter 3. Once again, we emphasise that the inferred galaxy starlight metallicities are uncertain due to the above caveats. Fig. 4.8 shows the CaT index as a function of the semi-major axis equivalent radius (as per Equations 3.3 and 3.4 of Chapter 3). The \(\text{CaT}_{F09}\) gradient is found to be essentially flat at all probed radii indicating an undetectably small radial change in metallicity.

The V03 SSP models predict that the CaT features saturate at a metallicity of roughly \([\text{Fe/H}] \approx -0.5\) dex such that there is a maximum allowed \(\text{CaT}_{F09}\) value of 6.18 Å. This theoretical behaviour has not been confirmed observationally. Our galaxy \(\text{CaT}_{F09}\) data are consistent with a saturation around 6.18 Å. Because our data scatter about this limit we cannot confidently use the V03 models to convert our \(\text{CaT}_{F09}\) values into metallicity. It is possible however that, as the colours suggest, the metallicity variation in the radial range probed is small (only \(\Delta[\text{Fe/H}] \sim 0.2\) dex) and thus a variation in \(\text{CaT}_{F09}\) may be hard to detect within the uncertainties. Indeed, between 20 and 80 arcsec, where the vast majority of our CaT data lies, both the colours and \(\text{CaT}_{F09}\) values are consistent with the predicted saturation limit.

\(^2\)This is different from the saturation value for \(\text{CaT}_{F10}\) because \(\text{CaT}_{F09}\) is an altogether different index. Therefore, the absolute values of the two CaT indices used in this Thesis for GC and galaxy light spectra cannot be directly compared.
Chapter 4. Global Properties of ‘Ordinary’ Early-type Galaxies: photometry and spectroscopy of stars and globular clusters in NGC 4494

Figure 4.8: Panels (a) and (b) show the $CaT_{F09}$ index and $(g-i)_0$ colour gradients of the NGC 4494 stellar light, respectively. Thin dashed lines show the saturation limit predicted by the V03 SSP models (i.e., $CaT_{F09} = 6.18$ Å or $[Fe/H] \sim -0.5$ dex). Thick solid line in Panel (a) is a rolling average. Panel (c) is a colour histogram of the photometric sample of GCs with $i_0 < 23.5$ mag and $(g-i)$ conversion to metallicity as per Sinnott et al. (2010).

4.3.2 Globular cluster system

GC colours and candidate selection

As described in Section 4.2.1, we have a combination of both HST/WFPC2 and Subaru/Suprime-Cam imaging available. Various selections are applied to identified point sources in order to avoid contamination by foreground stars and background galaxies. We first apply an upper size cut in both the HST (see Larsen et al., 2001) and the Subaru images³ (see Section 4.2.1) in order to remove clearly extended objects such as background galaxies. We also apply a spatial cut removing all objects beyond 8 arcmin ($\sim 10r_e$) from the galactic centre to avoid further contamination that dominates beyond that radius (see 4.3.2). Our colour selections are as follows: (1) whenever HST imaging is available, GC candidates are selected based on $(V-I)_0$ colours only. (2) If HST imaging is not available, the selection is based on a colour-colour cut in $(r-i)_0$ vs $(g-r)_0$ space from Subaru photometry (see Fig. 4.9). We

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³The size cut based on Subaru is only applied to objects beyond galactocentric radii of 0.5 arcmin because of crowding issues.
4.3. Analysis and results

Figure 4.9: Visual representation of our applied colour-colour selection for objects with galactocentric radii < 8 arcmin brighter than $i_0 = 23.5$ mag. Filled green star symbols are spectroscopically confirmed GCs while hollow red stars show our photometrically selected GC candidates. Solid line is the inferred GC sequence (i.e., $(g - r)_0 = 1.450(r - i)_0 + 0.142$). Spectroscopically confirmed stars (orange asterix) and emission line galaxies (orange filled circles) observed either as contaminants or fillers are shown, while other objects are shown in black.

Fit for the linear bisector (Feigelson and Babu, 1992) in colour-colour space using the spectroscopically confirmed GCs (i.e., $(g - r)_0 = 1.450(r - i)_0 + 0.142$) and allow for three times the intrinsic scatter about that line ($\sigma = 0.05$) for objects with $0.60 \leq (g - i)_0 \leq 1.20$, $0.05 \leq (g - r)_0 \leq 0.75$ and $0.20 \leq (r - i)_0 \leq 0.40$. Objects whose photometric uncertainties are sufficiently large to overlap with the above selection ranges are also kept as GC candidates. The final master GC catalogue of Subaru and HST photometry includes 431 selected GC candidates brighter than $i_0 = 24$. This catalogue is available online with Foster et al. (2011).

Selecting bright objects in common between the HST and Subaru images beyond a galactocentric radius of 0.5 arcmin to avoid Subaru image artefacts, we obtain the following colour conversion:

$$(g - i)_0 = 1.23 \times (V - I)_0 - 0.25$$ (4.7)
Chapter 4. Global Properties of ‘Ordinary’ Early-type Galaxies: photometry and spectroscopy of stars and globular clusters in NGC 4494

with an rms= 0.035 using a linear bisector fit [Feigelson and Babu, 1992]. We use this conversion to convert HST \((V-I)_0\) colours into \((g-i)_0\) to merge with the Subaru photometry.

The final colour magnitude diagram (CMD) for all our GC candidates with \(i_0 < 24\) mag is shown in Fig. 4.10. Three bright objects \(i_0 < 19.4\) mag) have recession velocities consistent with that of NGC 4494 but their absolute luminosity \((M_i < -10.9\) mag) suggests they fit within the definition of UCDs, or equivalently, dwarf-globular transition objects (DGTOs, see Section 4.3.2). All three UCDs are centrally located (within 2 arcmin or \(\sim 4r_e\) of NGC 4494’s centre). Other bright objects \(i_0 < 19.4\) mag) with colours consistent with the NGC 4494 GCs are uniformly distributed across the Subaru/Suprime-Cam field-of-view (19\times15 arcmin) suggesting that they are likely contaminant foreground stars. For this reason we apply a bright magnitude cut at \(i_0 = 19.4\) mag.

We check for the usual colour bimodality within our GC candidates in the combined HST and Subaru \((g-i)_0\) colour distributions. We apply the KMM (Ashman et al., 1994) test for the heteroscedastic (unequal widths) case to our GC candidates with \(i_0 < 23.5\) mag. The colour histogram and fit results are shown in Fig. 4.10. The returned p-value is < 0.0001, suggesting that a bimodal colour distribution is strongly favoured over a unimodal one at the > 99.99 per cent level. The peaks for the blue and red GCs are at \((g-i)_0 = 0.84\) and 1.07, with widths of \(\sigma = 0.084\) and 0.051, respectively. For comparison, Larsen et al. (2001) find peaks at \((V-I)_0 = 0.90\) and 1.10, corresponding to \((g-i)_0 = 0.86\) and 1.10, for the blue and red subpopulations when using the homoscedastic test on the HST data only. These small discrepancies are likely due to the intrinsic differences between the datasets (HST vs Subaru), possible intrinsic radial colour gradients (e.g., Harris, 2009b; Forbes et al., 2011) and methods (homoscedastic vs heteroscedastic). Larsen et al. (2001) also infer a relatively equal number of GCs in each subpopulation.

We choose to apply a nominal colour split at \((g-i)_0 = 0.99\), corresponding to \((V-I)_0 \sim 1.01\) based on the KMM results in order to separate the blue and red GCs. Using the Sinnott et al. (2010) conversion from \((g-i)_0\)-colour to metallicity, we infer that our colour split corresponds to a metallicity of \([Fe/H] \sim -0.68\) dex.
4.3. Analysis and results

**GC spatial distribution**

We construct projected surface density profiles of the NGC 4494 GC system candidates. Independent photometric selection criteria (as described in Section 4.3.2) are applied to both the HST and Subaru datasets to generate GC catalogues for this analysis. Between 1 and 4 arcmin, there are reliable surface density data for both Subaru and HST GC catalogues. Within the uncertainties the Subaru profile agrees with the HST profile, as shown in Figure 4.11.

We fit the GC density profile \( (N(r)) \) with a Sérsic profile (Sérsic, 1963) similar to that commonly done for galaxy surface density profiles and recently extended to GC systems (Peng et al., 2011). We fit the following variation of eq. 1 from Graham and Driver (2005):

\[
N(r) = N_e \exp \left( -b_n \left[ \left( r/R_e \right)^{1/n} - 1 \right] \right) + b_g, \tag{4.8}
\]

where \( b_n = 1.9992n - 0.3271 \). Free parameters recovered are the Sérsic index \( (n) \) of the GC system, which is a measure of the steepness of the profile, the effective radius of the GC system \( (R_e) \), which gives us a measure of the extent of the GC system, the surface density at that radius \( (N_e) \) and the background or contamination level \( (b_g) \). The results of the fits are shown in Fig. 4.11 and Table 4.2. For comparison with previous studies, we also fit a Power-law profile (i.e., \( N(r) \propto r^\alpha \)). We obtain slopes of \( \alpha = -1.7 \pm 0.2, -1.8 \pm 0.2 \) and \( -2.2 \pm 0.3 \) for all, blue and red GCs, respectively. As with other galaxies (e.g., Forbes et al., 1998a; Dirsch et al., 2003; Bassino et al., 2006), the red GCs are more centrally concentrated than the blue GCs. This is also inferred from their respective effective radii \( (R_{e, \text{blue}} = 138 \text{ arcsec} \) and \( R_{e, \text{red}} = 83 \text{ arcsec} \)).

We use 500 Monte Carlo realisations to estimate the total number of GCs based on the best fit Sérsic parameters and their covariance matrix by separately integrating the density profiles for all, the blue and the red GCs to infinity. We also explicitly account for completeness and contamination. This yields an estimated number of GCs of \( 392 \pm 49, 324 \pm 74 \) and \( 125 \pm 10 \) for all, red and blue GCs, respectively. Therefore, assuming \( m_V = 9.70 \) (RC3) as total galaxy magnitude and using other variables as per Table 4.1, the specific GC frequency \( S_N \) (Harris and van den Bergh, 1981) is \( 1.2 \pm 0.3 \), while \( T_N \) (Zepf and Ashman, 1993) is \( 4 \pm 1 \). This is
Figure 4.10: CMDs (top panel) for our GC candidates beyond 0.5 arcmin from the galactic centre selected based on Subaru (hollow circles) and HST (filled circles) imaging. All spectroscopically confirmed GCs around NGC 4494 are shown as crosses. Typical Subaru uncertainties are shown on the right hand side of the top panel. Lower panel shows histograms for our candidates brighter than $i_0 = 23.5$ mag (hollow) with KMM fits for each/the sum of the two subpopulations as solid/dashed grey line(s) and confirmed (filled histogram) GCs. The colour distribution of the confirmed GCs is representative of that of the candidates. The dotted line represents our fiducial colour split.
4.3. Analysis and results

Figure 4.11: Surface density profiles of the NGC 4494 GC system. All, red and blue subpopulations are shown in black, red and blue, respectively. Open and filled symbols show the HST and Subaru data, respectively. Sérsic fits with and without background/contamination constant (see text) are shown as dotted and solid lines, respectively. Also shown are scaled and offset Sérsic profile fits to the galaxy surface brightness profiles in the $g$- and $i$-bands ($\mu_i$) as labelled (see Section 4.3.1 and Fig. 4.4).

somewhat low for galaxies of similar stellar mass but still within the observed range
(see Spitler et al., 2008b; Peng et al., 2008).

It has recently been shown that the correlation between total number of GCs and the central black-hole mass (Spitler and Forbes, 2009) is tighter than other previously observed correlations with black-hole mass (see Burkert and Tremaine, 2010; Harris and Harris, 2011; Snyder et al., 2011). Therefore, using equation 3 of Harris and Harris (2011), we estimate that the mass of the central black-hole in NGC 4494 is $(1.6 \pm 0.2) \times 10^8 M_\odot$.

GC kinematics

For the candidate GCs that have available spectra with sufficient signal-to-noise ratio, we first measure their recession velocity. We use the IRAF task RV.FXCOR to cross-correlate the spectra with the 13 stellar templates described in Section 2.2.2.
### Table 4.3: Compilation of salient GC kinematic properties in the literature for selected large ETGs (column 1). Rotation amplitudes for all, blue and red GCs are given in columns 2, 5 and 8, respectively. The position angle of the rotation for all, blue and red GCs are given in columns 3, 6 and 9, respectively. Photometric position angles for each galaxy can be found in Table 4.1. The velocity dispersion for all, blue and red GCs are shown in columns 4, 7 and 10, respectively. The number of GCs in the kinematic sample for each study is shown in column 11. References in column 12 correspond to Côté et al. (2003, C03), Hwang et al. (2008, H08), Côté et al. (2001, C01), Schuberth et al. (2010, S10), Romanowsky et al. (2009, R09), Bergond et al. (2006, B06), Lee et al. (2010, L10) and Woodley et al. (2010a, W10a).

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<th>( P_{\text{rot,blue}} ) (deg)</th>
<th>( \sigma_{\text{blue}} ) (km s(^{-1}))</th>
<th>( V_{\text{rot,red}} ) (km s(^{-1}))</th>
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<th>( \sigma_{\text{red}} ) (km s(^{-1}))</th>
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Notes: Table 4.3: Compilation of salient GC kinematic properties in the literature for selected large ETGs (column 1). Rotation amplitudes for all, blue and red GCs are given in columns 2, 5 and 8, respectively. The position angle of the rotation for all, blue and red GCs are given in columns 3, 6 and 9, respectively. Photometric position angles for each galaxy can be found in Table 4.1. The velocity dispersion for all, blue and red GCs are shown in columns 4, 7 and 10, respectively. The number of GCs in the kinematic sample for each study is shown in column 11. References in column 12 correspond to Côté et al. (2003, C03), Hwang et al. (2008, H08), Côté et al. (2001, C01), Schuberth et al. (2010, S10), Romanowsky et al. (2009, R09), Bergond et al. (2006, B06), Lee et al. (2010, L10) and Woodley et al. (2010a, W10a).
Thus, for each GC we have 13 measured recession velocities together with output uncertainties from the FXCOR routine. The recession velocities available in Foster et al. (2011) are the average measured recession velocities using all 13 template cross-correlation results. The quoted uncertainties for the GC recession velocities are the maximum between 5 km s$^{-1}$ or the average output uncertainties given by FXCOR, which correspond to the average width of the cross-correlation peaks, added in quadrature to the standard deviation among the templates, which is an estimate of the systematics. Some of our spectra cover sufficiently blue wavelengths to use the H$_\alpha$ feature at 6563 Å to confirm the measured recession velocity. Some of our spectra were from Galactic stars and background emission line galaxies. An online table showing the position of those contaminants and their recession velocity is available (see Foster et al., 2011).

The spatial distribution of kinematically confirmed GCs is shown in Fig. 4.1. We look for rotation in the GC system around NGC 4494. We extend the kinemetry method described in Section 4.3.1 to discrete velocities and perform rolling radial fits for the amplitude of the rotation ($V_{\text{rot}}$), the velocity dispersion ($\sigma$) and the kinematic position angle ($PA_{\text{kin}}$) simultaneously. Rolling fits are performed by first using the inner $N_{\text{bin}}$ GCs to fit the kinemetry, then removing the innermost point and adding the next further point to refit the kinemetry, and so on, until all GCs have been exhausted. Gaussian line-of-sight velocity distributions are assumed. In practice, for the $j^{\text{th}}$ radial bin we minimise the likelihood ratio ($\Lambda_j$):

$$
\Lambda_j \propto \sum_{i=1}^{i=N_j} \left[ \frac{(V_{\text{obs},i} - V_{\text{mod},i,j})^2}{(\sigma_j^2 + (\Delta V_{\text{obs},i})^2)} + \ln(\sigma_j^2 + (\Delta V_{\text{obs},i})^2) \right],
$$

(4.9)

where $V_{\text{mod},i,j}$ is again given by Eq. 4.3 with $q_{\text{kin},j} = q_{\text{phot}} = 0.87$. Symbols $PA_i$, $V_{\text{obs},i}$ and $\Delta V_{\text{obs},i}$ are the position angle, recession velocity and uncertainty on the recession velocity for the $i^{\text{th}}$ GC, respectively. We assume that the kinematic axis ratio of the GC system is equal to the photometric axis ratio of the galaxy light because the GC kinematic data do not constrain the kinematic axis (i.e., $q_{\text{kin},j}$) ratio well.

Uncertainties on the fits to the GC kinematics are obtained using a bootstrap-

\footnote{We fix $PA_{\text{kin}} = PA_{\text{phot}} = 173$ degrees to get a better handle on the red GC kinematics since the rotation is low (see text).}
Figure 4.12: GC velocity distribution of the blue (hollow blue symbols), red (filled red symbols) GCs and UCDs (star symbols) recession velocities as a function of position angle (left panel) and galactocentric radius (right panel). Solid and dashed blue/red lines show the kinematic fit results and $\pm 2\sigma$, respectively, for the blue/red GC subpopulation. Blue/red dotted lines show $2\times$ the velocity dispersion (corrected for rotation) intervals for the blue/red GC subpopulation. Black dashed line represents NGC 4494’s systemic velocity. The photometric position angle is $PA_{\text{kin}} = 173$ degrees.
ping method similar to that used by Côté et al. (2001). Basically, we obtain 1000 “mock” GC kinematic samples of 109 GCs (our actual sample size) by sampling with replacement from our measured distribution and fit each mock sample. The quoted uncertainties are the 68% confidence interval inferred from the mock fits.

We also notice that this method tends to enhance the estimated rotation value when the position angle varies as a free parameter. We used Monte Carlo methods to quantify this bias. We find that $V_{\text{rot}}$ estimated using the above method on a sample of the same bin size and known slow rotation ($V_{\text{rot}} < 10 \text{ km s}^{-1}$) can be enhanced by as much as 20 km s$^{-1}$ when $P_{\text{A kin}}$ is allowed to vary freely. This bias sharply reduces to $\lesssim 5 \text{ km s}^{-1}$ for known input $V_{\text{rot}} > 50 \text{ km s}^{-1}$. For this reason, fixing $P_{\text{A kin}}$ to a reasonable value is recommended whenever possible to avoid this bias, especially when the output $V_{\text{rot}}$ is low.

We find that the kinematic position angle for the blue GCs ($170_{-14}^{+16}$ degrees) is consistent with the photometric position angle in the inner parts of the galaxy measured by N09 (i.e., $P_{\text{A phot}} \sim 178$ degrees, see Fig. 4.6). As will be discussed in great detail below, the red GCs show lower rotation, making the determination of the kinematic PA highly uncertain and artificially enhancing $V_{\text{rot}}$. Therefore, we fix the position angle to the photometric position angle (i.e., $P_{\text{A kin},j} = P_{\text{A phot}}$) for both subpopulations in order to better constrain the other parameters. The resulting fits for our fiducial colour split are shown in Fig. 4.12 for the whole sample and rolling fits as a function of radius can be found in Fig. 4.6 for both GC subpopulations. We exclude GC88 from the radial rolling fits as its position at $> 8r_e$ skews the measured rolling radius significantly. This does not change the amplitude of the fitted parameters significantly. We find significant major-axis rotation at all radii for the metal-poor GCs only with $41 \lesssim V_{\text{rot}} \lesssim 95 \text{ km s}^{-1}$ (see Fig. 4.6). The metal-rich subpopulation may not show significant rotation as $V_{\text{rot}}$ is consistent with 0 km s$^{-1}$ at most radii. To test the effect of our colour split assumption, we perform rolling fits as a function of $(g - i)_0$ colour, which we show in Fig. 4.13. These demonstrate that intermediate colour GCs (i.e., $0.90 < (g - i)_0 < 0.98$), in particular, do not show significant rotation and that this results in a higher uncertainty on the kinematic position angle. On the other hand, the reddest GCs ($(g - i)_0 > 0.98$) tentatively show some rotation. In every case we find that the velocity dispersion ($\sigma$) of all subpopulations are consistent with each other (see Fig. 4.6).
Figure 4.13: Rolling colour fits to the GC kinematics. Two cases are presented: $PA_{\text{kin}} = PA_{\text{phot}}$ (left panels) and variable $PA_{\text{kin}}$ (right panels). Shaded areas represent 68 per cent confidence intervals.
4.3. Analysis and results

GC metallicities

We are able to measure spectroscopic metallicities for 54 individual GCs and the three UCDs around NGC 4494. We use the method described in Chapter 2 to convert $CaT_{F10}$ into a metallicity. We emphasise that this $CaT_{F10}$ is different from $CaT_{F09}$ used above for galaxy spectra, which has broader passbands to accommodate the broadening of the CaT features due to large velocity dispersion in galaxies.

Fig. 4.14 shows our measured $CaT_{F10}$ index as a function of $(g-i)_0$ colour. We keep multiple $CaT_{F10}$ measurements of individual objects as separate data points. Predictions from the V03 and BC03 simple stellar population models are overlaid for comparison.

There are several immediately striking features in Fig. 4.14. First of all, the correlation between the $CaT_{F10}$ and colour is obvious and consistent with linear, albeit with large observational scatter. There is one outlier, namely the faint $(i_0 = 21.8)$ red GC, GC102. There is nothing obviously wrong with the photometry or spectrum (fitted or raw) of GC102, so we cannot explain the position of this (low signal-to-noise) outlier in Fig. 4.14.

The bulk of the GC data lie above the BC03 single stellar population models and close to those of V03 (for bluer colours). The apparently linear relationship found in NGC 4494 data up to the reddest colours are in contrast to the findings of Chapter 2 for the giant E galaxy NGC 1407, where the generally redder data follow the 13 Gyr V03 model track more closely at all colours. Many blue/red GCs in NGC 1407 have higher/lower measured $CaT_{F10}$ indices than the NGC 4494 GCs. We discuss this discrepancy and its implications for using the CaT as a metallicity indicator for extragalactic GCs in Section 4.4.

Finally, there appears to be a concentration of GCs with $CaT_{F10} \sim 6.5$ Å (or [Fe/H] $\sim -0.9$ dex). While our sample of spectroscopic GC metallicities is rather small for inferring the global properties of the distribution of GC metallicities in NGC 4494, it appears to be single peaked despite exhibiting clear $(g-i)_0$ colour bimodality (KMM yields a p-value of 0.002 for the confirmed GC sample). We note however that KMM is less reliable for small samples (see Ashman et al., 1994). Nevertheless, it is puzzling that the peak in the CaT distribution corresponds to the trough of the colour distribution (see Fig. 4.14). This result is reminiscent of that obtained for NGC 1407 (Chapter 2) and Caldwell et al. (2011), where the
Figure 4.14: $CaT_{F10}$ and inferred metallicity (right $y$-axis) as a function of colour for GCs (filled circles) and UCDs (hollow triangles) around NGC 4494. The top $x$-axis shows the linear colour to metallicity ($[Fe/H]_{S10}$) conversion of Sinnott et al. (2010). All repeat $CaT_{F10}$ measurements of individual objects are shown. Histograms for each axis are also shown. One outlier (highlighted with a large hollow circle) is discussed in the text. Predictions from the single stellar population models of V03 (black) and BC03 (grey) are shown for 5 (dotted line), 9 (dashed line) and 13 (solid line) Gyr.

clear colour bimodality also translated into a skewed single-peaked spectroscopic metallicity distribution.

Three UCDs around NGC 4494

As briefly mentioned in Section 4.3.2, we report the discovery of 3 spectroscopically confirmed UCDs (Drinkwater et al., 2000) associated with NGC 4494. We adopt a magnitude definition for UCDs of $M_i < -10.9$ mag, roughly equivalent to that adopted by Evstigneeva et al. (2008, $M_V < -10.3$). The 3 UCDs have absolute $i$-band magnitudes of -11.88, -11.92 and -11.71 mag, well within the range for UCD luminosities. Most UCDs have typically been found in dense cluster environments
4.3. Analysis and results

although, for example, one UCD has been confirmed around the Sombrero galaxy (Spitler et al., 2006; Hau et al., 2009), a spiral galaxy in a low-density environment. Another relevant example is that of NGC 5128, also an \( L^* \) early-type galaxy, wherein several possible UCDs may have been found (Taylor et al., 2010).

There is ongoing discussion in the literature about the origin and definition of UCDs. Popular formation scenarios propose that UCDs are either (1) the bright end of the compact star cluster (i.e., GC) luminosity function (e.g., Mieske et al., 2004), or (2) the slightly more extended remnants of tidally stripped dwarf galaxies (Bekki et al., 2003). Of course, both scenarios may occur (see Da Rocha et al., 2011; Norris and Kannappan, 2011). We thus examine the properties of the UCDs around NGC 4494 in order to determine their most likely origin.

UCD1 and UCD2 are within the HST imaging. We measure their sizes using \( \text{ishape} \) (Larsen, 1999) and obtain 1.7 ± 0.4 pc and 2.3 ± 0.6 pc for UCD1 and UCD2, respectively. We are unable to obtain a size estimate for UCD3 as it is unresolved on the Subaru image. Therefore, at least two of the three UCDs around NGC 4494 are compact, as predicted by the star cluster origin scenario. In fact, they are unusually compact when compared to other objects generally classified as UCDs, which usually show a clear size-luminosity relationship. This again may indicate that there exists various classes of UCDs with distinct formation channels. All three UCDs have high CaT-inferred metallicities (\(-0.3 \, \text{dex} \gtrsim [Fe/H] \gtrsim -0.4 \, \text{dex}\)) as is also the case for some other UCDs (e.g., Evstigneeva et al., 2007). UCD1 is detected with Chandra in the X-ray (Humphrey and Buote, 2008, object id NGC_4494_CXOU_12:3125.5+254619) with \( L_X = (2.1 \pm 1.1) \times 10^{38} \, \text{ergs s}^{-1} \). This X-ray luminosity is consistent with the presence of low mass X-ray binary stars in UCD1.

Following Da Rocha et al. (2011), we compute the number of expected GCs brighter than \( i_0 = 19.3 \, \text{mag} \) (i.e., the magnitude of our faintest UCD candidate) around NGC 4494 assuming that UCDs around NGC 4494 are simply the bright end of its GC system. We use the total number of GCs and the GC luminosity function (Kundu and Whitmore, 2001) to estimate that \( 2 \pm 2 \) UCDs are consistent with being the bright extension of the GC system. Thus, under these assumptions, our 3 confirmed UCDs brighter than \( i_0 = 19.3 \, \text{mag} \) around NGC 4494 are consistent with representing the bright end of the GC luminosity function. We conclude that
there is no need to invoke another formation channel such as tidal stripping of dwarf galaxies (e.g., Da Rocha et al., 2011; Norris and Kannappan, 2010) for the UCDs around NGC 4494.

4.4 Discussion

In this section, we compare the observed properties of NGC 4494 with the predictions from theoretical models in order to get an understanding of its formation.

4.4.1 Inferences from the stellar light

In Section 4.3.1 we report a ‘flattening’ of the stellar kinematics of NGC 4494 with radius such that the kinematics become more disky at large radii. In other words, at large radii only the stars close to the semi-major axis show rotation such that the kinematic axis ratio $q_{\text{kin}}$ is low. This is supported by the observed anti-correlation between $h_3$ and $(V_{\text{obs}} - V_{\text{sys}})/\sigma$, which indicates the presence of a disk-like structure. However, it contrasts with the stellar surface brightness of the galaxy, which has a very constant and relatively round profile at all radii. This kinematic flattening at large radii may be related to the transition suggested by Hoffman et al. (2010) between 1-3 $r_e$, where the kinematic signature of the progenitors’ disk stars survived. However, it is a puzzle as to how such a ‘kinematic’ disk at large radii could be invisible in the imaging data. Indeed, the axis ratio of kinematic sub-structures are usually found to agree with that of the stellar distribution (e.g., Krajnović et al., 2008).

The stellar populations don’t show any hint of a flattened distribution either. Denicoló et al. (2003) reported a central age of 6.7 Gyr with a central metallicity of $[Fe/H] \approx +0.03$ dex for NGC 4494 and Chapter 3 finds no evidence for radial metallicity variations with metallicities roughly constant around $[Fe/H] \geq -0.5$ dex between $\sim 0.2$ and $1.4r_e$. In this Chapter, we find no azimuthal variations in the measured CaT index values (see Fig. 4.8) or colour. The CaT gradient suggests that the luminosity weighted metallicity of the NGC 4494 stars is either higher than $\sim -0.5$ dex from $0.2r_e$ all the way out to at least $\sim 1.6r_e$ and/or that the metallicity gradient is undetectably shallow for the CaT method. The colour gradient in the
same radial range suggests a moderate metallicity gradient of \( \sim -0.17 \pm 0.02 \) dex per dex.

We look at the departure of NGC 4494 from the fundamental plane of ETG (e.g., Djorgovski and Davis, 1987; Dressler et al., 1987) using the method of Forbes et al. (1998b). We compute \( R = 2 \log \sigma_0 + 0.286 M_B + 0.2 \mu_e - 3.101 \). Values for the central velocity dispersion (\( \sigma_0 \)), the total \( B \)-band magnitude (\( M_B \)) and the \( B \)-band surface brightness at \( r_e (\mu_e) \) are taken from the Hyperleda database. We obtain \( R \sim -0.37 \), indicating that NGC 4494 falls below the fundamental plane of ETGs. Such a low value for \( R \) is usually observed for morphologically disturbed galaxies such as obvious merger remnants and is usually associated with young central ages (\( \sim 1.5 \) Gyr). While such a young central age is unlikely based on both the red central colour and the spectroscopic age reported by Denicoló et al. (2005) for NGC 4494, it may be an indication that it has gone through a recent interaction.

Recently, the SAURON team reported the results of their 2D stellar population analysis on 48 early-type galaxies (Kuntschner et al., 2010). They find that flattened structures in the images of fast-rotators (Emsellem et al., 2007; Krajnović et al., 2008) with disky kinematics have distinct stellar populations, while galaxies classified as slow rotators, and sometimes harboring inner kinematically decoupled cores, show no clearly distinct stellar population variation. NGC 4494 does not appear to fit either of those categories. At small radii \( \sim 0.1 r_e \), the kinematically decoupled core suggests it is a slow-rotator. At all other radii, its increasingly flattened kinematics suggest it is a fast rotator, but as stated above we find no evidence for a flattening of the stellar distribution or of distinct stellar populations from either the \( CaT_{F09} \) or the modelling of the surface brightness profile and colours. In any case, transitions between slow and fast rotators at large radii may be common as P09 also report a transition from a fast to a slow rotator beyond the SAURON field-of-view in NGC 821. Again, these may be the first observational evidences for the transitional kinematics expected to occur between 1 and 3\( r_e \) in major merger remnants (Hoffman et al., 2010).

In Fig. 4.15, we plot a standard \( \langle V_{rot}/\sigma \rangle \) vs \( \epsilon = 1 - q_{phot} \) diagnostic diagram (Cappellari et al., 2007). This plot can be used to diagnose both the intrinsic structure of the galaxy (in particular NGC 4494) and the nature of the merger. We

\(^5\)http://leda.univ-lyon1.fr
Figure 4.15: Azimuthally averaged rotation \( \langle V_{rot}/\sigma \rangle \) versus ellipticity \( (\epsilon = 1 - q_{phot}) \) diagnostic diagram, after Cappellari et al. (2007). Data points represent the central regions of nearby ETGs classified as ‘fast-rotators’ from the SAURON and ATLAS3D surveys. The green dashed curve shows a theoretical prediction for edge-on oblate isotropic rotators, and the magenta dotted curve shows the inferred edge-on average relation for nearby fast-rotators. The observed position of NGC 4494 in the diagram is labelled, with a solid black curve showing the path of possible intrinsic values for a sequence of different assumed inclination angles.

have highlighted NGC 4494 on this diagram showing the ATLAS3D data (Emsellem et al., 2011). The green curve in Fig. 4.15 represents an oblate isotropic rotator seen edge-on, and the magenta curve shows what is typical for an edge-on fast rotator after modelling the dynamics of the SAURON sample as inferred by Cappellari et al. (2007). Because galaxies are generally observed below the green curve, this suggests that they are not isotropic. These results allow us to derive a best-guess solution for the inclination of any fast rotator (including NGC 4494) by assuming that its internal anisotropy follows the mean trend of the other galaxies. We can also thereby estimate the ellipticity and \( \langle V_{rot}/\sigma \rangle \) values that would be obtained if the galaxy was viewed edge-on.

The black curve shows the track of possible edge-on values for NGC 4494 for a series of different inclinations, where we note that the dependence of the disper-
4.4. Discussion

The intersection of the black curve with the magenta curve then represents the self-consistent solution for NGC 4494 under the SAURON-based anisotropy assumption. From this we conclude that NGC 4494 is most likely (but not definitively) a flattened galaxy ($q_{\text{phot}} \sim 0.6$) seen at an inclination of $\sim 45$ degrees. It may even be an S0 rather than a bona fide E. The uncertainties here are driven not by the measured parameters (which are determined very precisely) but by the intrinsic scatter in the anisotropy-ellipticity relation. To estimate this, we use the spread of observed galaxies to the right of the magenta curve in Fig. 4.15. This suggests an intrinsic ellipticity uncertainty of $\sim \pm 0.2$, and an inclination between 39 and 90 degrees. Similarly, using 2D dynamical modelling of NGC 4494, Rodionov and Athanassoula (2011) found that a $\sim 45$ degrees inclination may be preferred. If this interpretation is correct, then to recover edge-on $V_{\text{rot}}$ estimates, all of our velocity estimates should be increased by $\sim 40$ per cent.

4.4.2 Inferences from the GC system

We find that the GC colour subpopulations are reasonably well defined in NGC 4494 and choose a nominal colour cut at $(g-i)_0 = 0.99$ to delineate metal-poor from -rich GCs. The 54 spectroscopically measured GC metallicities vary between $-2.0 \lesssim [F e/H] \lesssim 0.0$ dex and their distribution appears single-peaked around $[F e/H]_{\text{mean}} \sim -1.0$ dex despite their clear bimodal colour distribution. A similar behaviour was found for GCs around NGC 1407 (Chapter 2) and M31 (Caldwell et al., 2011), while the distributions of GC spectroscopic metallicities around the Milky Way, NGC 4472 (see Strader et al., 2007) and NGC 5128 (see Woodley et al., 2010b) are bimodal. There is some recent spectroscopic evidence that the GCs around the Sombrero galaxy (M104, see Alves-Brito et al., 2011, but with low statistical significance) may also have a bimodal metallicity distribution. Taken at face value, these results may have some interesting implications for the ubiquity of the GC metallicity bimodality as inferred from GC colour distributions (also see Yoon et al., 2006; Peng et al., 2006; Blakeslee et al., 2010). However, as also mentioned in Chapter 2 the reliability of the CaT as a metallicity indicator needs to be better established before a definite statement can be made about the metallicity bimodality in NGC 4494 (and NGC 1407).
It has been suggested (and shown) that the distribution of red GCs usually follows that of the galaxy stars, while blue GCs follow the X-ray halo profile of their host galaxy (e.g., Minniti, 1996; Forbes et al., 2004; Boley et al., 2009). This suggestion is based on both model predictions and the similarities of the respective spatial distribution and abundances. Surprisingly, we find that the surface brightness profile of the stars does not compare well with the spatial distribution of the red (or the blue) GCs in NGC 4494 (see Fig. 4.11). Indeed, the Sersic index of the stars is inconsistent with that of both GC subpopulations, and this difference is even more pronounced for the red GCs. A similar conclusion is reached from comparing the kinematics of the stars, which agrees better with the blue GC kinematics than with that of the red GCs at the same radius (see Fig. 4.6). On the other hand, the colour of the galaxy stars is consistent with that of the red GCs (see Fig. 4.8). Therefore, the association of the red GCs with the galaxy stars is less clear in NGC 4494 than previously observed in other galaxies.

The V03 SSP models predict that the CaT saturates at high metallicity (i.e., \([Fe/H] = -0.5\) dex). This prediction is consistent with the distribution of the GC data for NGC 1407 in Chapter 2 but is less clear from Fig. 4.14 where the relationship between colour and \(CaT_{F10}\) appears linear at all probed metallicities. This is consistent with what has been observed in the Galactic GCs (AZ88). On the other hand, in Fig. 4.8 the measured \(CaT_{F09}\) for galaxy spectra scatters about a constant value, which coincides with the saturation value predicted by the V03 models. This may be interpreted as proof of the saturation prediction. However, the galaxy colour gradient (see Fig. 4.4) is shallow at similar radii suggesting that the expected change in \(CaT_{F09}\) may be small. In other words, the absence of a CaT radial gradient in the galaxy found in this and Chapter 3 may not prove the V03 saturation prediction. The question remains open.

Second, in Chapter 2 we found that the brightest blue and red GCs in NGC 1407 have the same CaT index value despite their wide separation in colour. This cast serious doubt on the reliability of the CaT as a metallicity indicator. Moreover, several fitted GC spectra across the range of GC luminosities probed around NGC 1407 showed Paschen lines. We find no such Paschen lines in the GC spectra for NGC 4494, which cover a comparable range in absolute luminosities. The presence of Paschen features in the GCs around NGC 1407 cannot be confirmed directly.
4.4. Discussion

Several possible explanations for these behaviours are put forward in Chapter 2, including the presence of hot blue stars such as BHB, BS or young stars mainly in the blue GCs whose Paschen lines might be affecting the CaT features. Another possibility is that the CaT may saturate at lower metallicity (i.e. $[Fe/H] \sim -0.8$ dex) than predicted by V03 or perhaps colour does not trace metallicity linearly (e.g., Yoon et al., 2006; Peng et al., 2006; Blakeslee et al., 2010).

Based on the results for NGC 4494 shown in Fig. 4.14, there is no clear evidence that the CaT saturates earlier than predicted by V03 or that the CaT behaves non-linearly with colour. In fact, the relationship between $(g-i)_0$ colours and $CaT_{F10}$ is consistent with being linear, albeit with large scatter. Some of this scatter is definitely related to observational uncertainties, however given the uncertainty in the current theoretical understanding of the behaviour of the CaT, we cannot rule out that other effects could yield to higher intrinsic scatter. For example, the strange distribution of $CaT_{F10}$ values in the GCs around NGC 1407 may be best explained by the presence of hot blue stars in a significant number of its GCs afterall.

In Section 4.3.2, we measure the rotational velocity and velocity dispersion of the blue and red GCs. In order to put our results into a broader context, Fig. 4.16 reproduces parts of figure 12 from Lee et al. (2010) using the updated kinematic data presented in Table 4.3 and compares GC kinematics with the global properties of the host galaxies for large ETGs. One caveat of the following comparison has to do with the heterogeneity of the methods used in the various dynamical studies represented in Fig. 4.16. Moreover, NGC 4494 is the only fast-rotator with large GC kinematic sample. Thus, its GC kinematics may be intrinsically different. Nevertheless, we find that NGC 4494 compares well with other large ETGs. We confirm that it agrees with the trends found between the velocity dispersion of the whole GC system and X-ray, central galactic velocity dispersion and $B$-band absolute magnitude as reported in Lee et al. (2010). However, the kinematics of the blue GCs of NGC 4494 appear to deviate from that of other large E galaxies in the $V_{\text{rot,blue}}/\sigma_{\text{blue}}$ vs $\sigma_{\text{star}}$ space, emphasising the large rotation of the blue GCs. Perhaps surprisingly given the arguably “unusually low” X-ray luminosity of NGC 4494, the GC kinematics agree well with the expected trend with galaxy X-ray luminosity (e.g., Romanowsky et al., 2003; O’Sullivan and Ponman, 2004). This also suggests that the processes
Figure 4.16: Comparison of salient GC kinematic properties with host galaxy global parameters: X-ray luminosity ($\log(L_X)$), stellar velocity dispersion ($\sigma_{\text{star}}$) and absolute $V$-band magnitude ($M_V$). Symbols on the y-axis and GC kinematics are from Table 4.3. We include literature GC kinematic studies (filled circles) and NGC 4494 data (hollow stars and upper limit symbols). Solid lines are bisector fits to correlated parameters from Lee et al. (2010, figure 12). Datum for NGC 4494 disagrees with the $V_{\text{rot, blue}}/\sigma_{\text{blue}}$ vs $\sigma_{\text{star}}$ trend observed in other large E galaxies (middle lower panel).
involved in the formation of NGC 4494 that led to its peculiar X-ray luminosity and kinematics have preserved the majority of the correlations between its global properties and its GC kinematics as with other large ETGs.

Assuming that NGC 4494 has indeed undergone a recent interaction as inferred by O'Sullivan and Ponman (2004) from its X-ray luminosity, then we may reasonably conclude that the bulk of its GC system formed before that interaction and is thus a conglomerate of the progenitors’ GC systems. Therefore, the current GC kinematics may hold clues to the understanding of the kinematics of the progenitor galaxies involved in the latest merger event. In this spirit, we use numerical simulations of disk-disk major mergers in order to see what can be learned about the progenitors from the GC kinematics. Details of the simulations and results are presented in appendix C of Foster et al. (2011). By studying numerous simulations of mergers with a variety of initial conditions, we find that the model that best reproduces the observed kinematics of the blue and red GCs (ignoring the intermediate colour GCs that show little rotation) involves a major disk-disk merger with a large amount of orbital angular momentum and a retrograde-retrograde orbital configuration. Models with other orbital configurations do not yield GC kinematics that are consistent with what is observed for NGC 4494. This is yet another suggestion that NGC 4494 may be a major merger remnant.

4.5 Summary and conclusions

NGC 4494 has often been dubbed an ‘ordinary elliptical’ galaxy, making it an ideal target for understanding the formation and evolution of a typical galaxy. In this Chapter, we combine imaging and spectroscopy of stellar light and GCs in NGC 4494. From the imaging we obtain the stellar surface brightness profiles and GC density profiles. We find that the colour distribution of the GC system around NGC 4494 is statistically better fitted by two Gaussians than a single one, suggesting metallicity bimodality. The spectroscopy yields spatially resolved kinematics and abundances of the stellar component and GCs. A total of 109 individual GCs and 3 UCD/DGTOs are confirmed spectroscopically. The properties of the UCDs are consistent with them being bright GCs. Metallicities are measured for 54 GCs and the 3 UCDs using the CaT absorption lines. The CaT inferred metallicity dis-
tribution for the GC system is single-peaked, in contrast to that inferred from the colours, which is clearly bimodal. Measurements for both the stellar light and GC spectroscopy can be found in Foster et al. (2011). We find that while the intermediate colour (green) GCs do not rotate, the blue (and possibly reddest) GCs do rotate (Fig. 4.13) as do the galaxy stars (Fig. 4.6). The velocity dispersion of all GC subpopulations and the galaxy stars are consistent.

A comparison of the GC system’s kinematics and the global properties of NGC 4494 with those of other large ETGs suggest that NGC 4494 is indeed typical with the exception of the unusually high blue GC rotation. We find suggestive evidence in the distinct kinematics for a possible third intermediate colour (green) GC subpopulation. We infer that most of the observational evidence suggests that NGC 4494 is consistent with a formation via a recent gas-rich major merger, but other formation scenarios cannot be ruled out. Some remaining open issues are:

1. the relatively old (6.7 Gyr) measured central age suggests that little dissipation and recent central star formation has occurred (i.e., possibly a dry merger). However, its cuspy surface brightness profile and the presence of a kinematically decoupled core suggest a high gas fraction of $\geq 15$ per cent (Hopkins et al., 2009; Hoffman et al., 2010). This is also supported by the presence of an inner dust ring (Xu et al., 2010). Therefore, the evidence is not conclusive as to the amount of gas dissipation involved in the formation of NGC 4494. The possibly ’unusually’ low X-ray luminosity suggests that the mechanism involved in depleting the gas must have allowed enough dissipation to form a kinematically decoupled core without significant recent central star formation.

2. The inner kinematic profile of NGC 4494 follows the light profile well up to $\sim 1.8 r_e$, beyond that the kinematics become increasingly flattened with radius (i.e., the axis ratio $q_{\text{kin}}$ is low). We find no evidence of a flattened component in the stellar distribution from our imaging. It is however not surprising to find transitions in the kinematics of merger remnants at 1-3$r_e$ as they are predicted in the models of Hoffman et al. (2010). We suggest that NGC 4494 may be a flattened galaxy ($q_{\text{phot}} = 0.6 \pm 0.2$), possibly even an S0, seen at an inclination of $45^\circ \pm 6^\circ$ degrees based on its position in the classic $\langle V_{\text{rot}}/\sigma \rangle$ vs $\epsilon = 1 - q_{\text{phot}}$ diagram (Fig 4.15). This may explain its high flattened rotation with round
4.5. Summary and conclusions

photometric isophotes.

Off-axis deep optical spectroscopy using long-slit out to large galactocentric radii would be ideal to independently test the flattened kinematics. It would also allow for a stellar population analysis (i.e., ages, metallicities and $\alpha$-element abundances) using the standard and well tested Lick system (e.g., Proctor and Sansom, 2002). The added knowledge of spatially resolved stellar ages and $\alpha$-element abundances may highlight distinct stellar populations as observed by SAURON (Kuntschner et al., 2010) that were not seen from our near-infrared spectra. While such data may be observationally challenging to acquire with the current generation of astronomical facilities, faint spectroscopy in the outskirts of galaxies could be tackled using the next generation of instruments and telescopes.
Conclusions

We have included an extensive discussion and our relevant conclusions in the previous Chapters. For this reason, the present Chapter simply summarises and highlights the main findings of this Thesis and their global consequences for galaxy formation and evolution. We also discuss our vision for future work in this area.

5.1 Summary

Recent theoretical studies of the formation and evolution of galaxies suggest that a variety of processes are important in shaping and determining the global properties of galaxies. For example, processes generally invoked in order to reproduce observational constraints within popular theoretical paradigms include galaxy mergers, dissipation of gas, and feedback from either stellar winds, SN or AGN (e.g., Croton et al., 2006; Naab et al., 2007; Hopkins et al., 2009; Hoffman et al., 2009, 2010). Galaxy formation models make predictions for the effects of these processes on the remnant galaxy’s stellar population distribution and kinematics but GC system modelling is less advanced. In this Thesis, we show how combined spectroscopic and imaging studies of stars and GCs in galaxies can help constrain those models.

In Chapter 2, we obtain a sample of 144 near-infrared integrated light spectra of GCs around the brightest group galaxy NGC 1407 to test whether the CaT index can be used as a metallicity indicator for extragalactic GCs. Different sets of single stellar population models make different predictions for the behaviour of the CaT as a function of metallicity. In Chapter 2, the metallicities of the GCs around NGC 1407 are obtained from CaT index values using an empirical conversion. The measured
CaT/metallicity distributions show unexpected features, the most remarkable being that the brightest red and blue GCs have similar CaT values despite their large difference in mean colour. Suggested explanations for this behaviour in the NGC 1407 GC system are:

- the CaT may be affected by a population of hot blue stars,
- the CaT may saturate earlier than predicted by the models, and/or
- colour may not trace metallicity linearly.

We conclude that until these possibilities are understood, the use of the CaT as a metallicity indicator for the integrated spectra of extragalactic GCs will remain problematic.

Chapter 3 describes how we obtain galaxy stellar light spectra out to large galactocentric radii using the SKiMS technique of P09 for DEIMOS. We also make use of the metallicity sensitive near-infrared CaT features together with SSP models to obtain metallicities. Our technique is applied as a pilot study to the three relatively nearby (≤ 30 Mpc) intermediate-mass to massive ETGs: NGC 1407, NGC 2768 and NGC 4494. Results are compared with previous literature inner region values and generally show good agreement. We also include a comparison with profiles from dissipational disk-disk major merger simulations. Based on our new extended metallicity gradients combined with other observational evidence and theoretical predictions, we discuss possible formation scenarios for the galaxies in our sample. We conclude that

- the CaT/metallicity gradient in NGC 1407 is consistent with a formation in which dissipation played a major role,
- while the gradient in NGC 2768 is well reproduced via a dissipational major merger scenario.
- We were unable to measure a CaT/metallicity gradient in NGC 4494, suggesting that the gradient is either too shallow for detection with this method or the CaT may saturate at a metallicity of $[Fe/H] \sim -0.5$ dex.

In Chapter 4 we combine the spectroscopic techniques of P09, Chapter 2 and Chapter 3 together with wide-field imaging of the galaxy NGC 4494 to carry one of
the most complete studies of an ordinary ETG galaxy and its GC system to date. We derive galaxy surface brightness and colour profiles out to large galactocentric radii. We compare the latter to metallicities derived using the near-infrared CaT. We obtain stellar kinematics out to \( \sim 3.5r_e \). The latter appear flattened or elongated beyond \( \sim 1.8r_e \) in contrast to the relatively round photometric isophotes. In fact, we conclude that NGC 4494 may be a flattened galaxy, possibly even an S0, seen at an inclination of \( \sim 45 \) degrees. A catalogue of 431 photometrically selected GC candidates brighter than \( i_0 = 24 \) is published. Of those candidates, 109 are confirmed spectroscopically to be bona fide GCs and 54 have measured spectroscopic metallicities. We also report the discovery of 3 spectroscopically confirmed UCDs around NGC 4494. Based on their compactness, metallicities and number, we conclude that they are consistent with being the bright end of the GC system. The metal-poor GCs are found to be rotating with similar amplitude as the galaxy stars, while the metal-rich GCs show only marginal rotation. We supplement our analysis with available literature data and results. Using model predictions of galaxy formation, and a suite of merger simulations, we find that many of the observational properties of NGC 4494 may be explained by a formation in a relatively recent gas-rich major merger.

In general, we find that two of the three galaxies discussed in this Thesis are consistent with a formation wherein major merging played a significant role, while NGC 1407 shows signs of a dissipative formation or possibly minor merging. We note that this is surprising given the respective environments of these galaxies. Indeed, NGC 1407 is a giant E galaxy and the brightest member of a large group. Therefore, it likely sits at the centre of a much deeper potential well than both NGC 2768 and NGC 4494, which have more modest sizes and reside in more typical environments. Under the current \( \Lambda \)CDM paradigm, galaxies like NGC 1407 are much more likely to have formed via a series of violent and major mergers than galaxies in less dense environments. It is possible that this apparent discrepancy is a result of our admittedly small sample and thus uncertainties due to small sample statistics apply. For this reason, we are careful not to draw strong conclusions based on such a small sample.

We provide a list of some of the main open questions relating to the work in this Thesis below.
1. Can the CaT be used reliably as a metallicity indicator and what is its dependence on HB and BS stars? Indeed, as discussed throughout this Thesis, theoretical models (e.g., V03, BC03) disagree as to the sensitivity of the CaT to metallicity, and the linearity of this relationship. On the other hand, AZ88 showed that the CaT in integrated light spectra of Galactic GCs varies linearly with metallicity. The results presented herein are still ambiguous on this topic.

2. Does the CaT saturate at high metallicity such that a maximum CaT index value is reached as predicted by the models of V03? The GC data for NGC 4494 presented in Chapter 4 clearly shows that several GC CaT values lie significantly above this predicted limit (see Fig. 4.14). However, the distribution of the NGC 1407 GC CaT data as a function of colour (see Fig. 2.12) and the apparently constant value of the CaT for the galaxy stellar light in NGC 4494 (see Fig. 4.8) seem to argue the other way.

3. Does the near ubiquity of the GC colour bimodality translate into a ubiquity in GC metallicities? The two galaxies for which we have looked at the spectroscopic metallicity distribution of their GCs do not show significant bimodality. This is ultimately tied to the reliability of the CaT as a metallicity indicator.

4. Is the blue tilt seen in the GC CMDs of most massive galaxies rightly interpreted as a mass-metallicity relation due to self-enrichment? We do see a blue tilt in the metallicity-luminosity space of the GCs around NGC 1407 (see Fig. 2.1), which would suggest that this interpretation is correct. However, since we are unable to confidently identify two metallicity subpopulations in this sample, it may not make sense to split the GCs into two subpopulations in the first place.

5. Are the red and blue GCs truly associated with the galaxy stars and X-ray halo, respectively? While several previous studies of the GC systems of galaxies seem to suggest that this is indeed the case (e.g., Minniti, 1996; Forbes et al., 2004; Boley et al., 2009), we do not find that this is obviously the case for the galaxy NGC 4494. We have studied both its stellar light component and GC system in great details and find that the spatial distribution of neither subpopulations follows the galaxy stellar light profile. Furthermore, the kinematics of the
5.2. Future work

galaxy stars are more consistent with the blue GCs kinematics than with those of the red GCs. On the other hand, it is possible that NGC 4494 is an outlier case. For this reason, large statistical samples of galaxies and their GC systems will help to answer this question more robustly.

6. Does the metallicity of the galaxy stellar light follow the isophotes of the galaxy? In Chapter 3, we assumed that this is the case. However, this assumption needs to be tested explicitly and, whatever the outcome, its implications clearly understood.

7. What are the various predictions of early dissipative collapse and hierarchical merger scenarios for the formation, stellar populations and kinematics of GCs and how do they contrast? Indeed, while galaxy formation scenarios make testable predictions for the observational properties of the galaxies themselves, GC modelling is still in its infancy and quantitative predictions are rare. For this reason, it is difficult to relate the observed properties of our GCs to galaxy formation models quantitatively and delineate between the various scenarios.

5.2 Future work

In order to answer the above questions, further observational and theoretical effort will be required.

The acquisition of the majority of the data presented in this Thesis was designed to obtain spectra of GCs only. Following the encouraging results of P09, Chapter 3 and Chapter 4, masks are now designed to be filled to capacity with dedicated galaxy stellar background slits in order to increase the radial and azimuthal coverage. This will enable better 2-dimensional mapping of the metallicity distribution and kinematics. This approach should yield results comparable to the works of e.g., Kuntschner et al. (2006), Rawle et al. (2008) and Emsellem et al. (2011), but reaching out to larger radii, thanks to the larger field-of-view of the DEIMOS spectrograph. Moreover, the assumption that the 2-dimensional metallicity distribution follows the isophotes could then be tested and its effect on the conclusions of Chapters 3 and 4 assessed.

Calibration and understanding of the behaviour of the CaT with metallicity,
BHB and BS stars can be achieved by looking at integrated light spectra of GCs in the local group (e.g., around the Milky Way or M31) wherein resolved CMDs of their individual member stars, and hence reliable stellar population parameters and HB morphologies are available. An alternate approach would be to obtain optical spectra, where stellar population parameters can be obtained reliably using well tested techniques such as that of Proctor and Sansom (2002), and compare those with inferred metallicities from the CaT for the same object. A reliable calibration of the CaT method would help answer the key questions about the existence and possible causes of the blue tilt and GC metallicity bimodality.

This Thesis has shown that extensive studies of individual galaxies incorporating many lines of evidence (e.g., imaging and spectroscopy of stars and GCs) can help disentangle the processes involved in the formation and evolution of selected galaxies. As such datasets become available, observational constraints based on large statistical samples will help improve our understanding of the details of galaxy formation and evolution as a whole. Indeed, large datasets are critical to help avoid uncertainties due to small number statistics and provide reliable observational constraints. For example, these would answer questions regarding the principal formation mechanisms involved in the formation of galaxies as a function of e.g. mass and environment, the association between galaxy stars and red GCs, the ubiquity of the GC metallicity bimodality, etc. Moreover, with the improvement of computing power, simulations are now starting to resolve and thus better able to make quantitative predictions for the formation and properties of GCs around galaxies. As more and more of those predictions become available, models can be compared against observational constraints in a more robust quantitative manner.

In this Thesis, we focus on a subset of 3 ETG selected from the SMEAGOL and the SAGES Legacy Unifying Globulars and Galaxies (SLUGG) surveys. The target selection for these galaxies was designed to select a “representative” sample of nearby ETGs. In total, 25 galaxies are selected, of which 9 have already been observed completely and 9 more have partial observations. These data, combined with the various techniques presented in this Thesis, will provide a statistical sample of observations of GC systems and their host galaxies that should greatly inform our understanding of GC and galaxy formation.

\footnote{http://sages.ucolick.org/surveys.html}
5.2. Future work

With the next generation of astronomical facilities such as the James Webb Space Telescope, the extremely large telescopes and the development of adaptive optics, the techniques employed in this Thesis can be used at higher redshift. We will be able to resolve stars in GCs for many more galaxies. The knowledge acquired through such data will be far reaching. For example, observations at high redshift could be compared to present day galaxies, and assumptions that for example GCs and stellar populations in external galaxies behave similarly to those around the Milky Way tested. Moreover, comparing high with low redshifts results, one can infer whether significant evolution has occurred.

To conclude, the work presented herein has shown how detailed studies of galaxies and their GC systems are an essential and robust observational tool for understanding the formation and evolution of structure and galaxies in the Universe.
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We use the method described in Cardiel et al. (1998) and in appendix A2 of C01 to compute the uncertainties on the raw indices ($CaT_{AZ88}$). For the $CaT_{F10}$ index measured on the template fitted spectra it is difficult to assess the uncertainties in our measurements and hence on the inferred metallicity exactly. This is because the template fitting procedure has modified the variance on each pixel in a nontrivial manner. While the fitting has essentially extrapolated across skylines, thereby minimising their effect on the final index measurements, it is unclear how the fits themselves may be affected by skyline residuals and noise. Adding to this is the possible introduction of uncertainties arising from the continuum fitting step.

For this reason, we model the uncertainty on our $CaT_{F10}$ measurements using Monte Carlo methods similar to that used by Emsellem et al. (2004) and Weijmans et al. (2009). We first measure the ‘exact’ $CaT_{F10}$ index value using our index measurement method (template and continuum fitting applied) on V03 SSP model spectra. These are then compared to $CaT_{F10}$ values measured on the same fitted spectra with added Poisson noise. The uncertainties as a function of signal-to-noise shown in Figure A.1 are the average difference between the two measurements. We find no trend between the uncertainties and metallicity.

The method detailed above does not describe our $CaT_{F10}$ uncertainties perfectly. Nevertheless, it follows our index computation scheme closely and should be a reasonable uncertainty estimate. This is supported by the fact that the scatter in the $CaT_{F10}$ and [$Fe/H$] distributions is similar to the size of the uncertainties. There is one caveat with these uncertainty estimates: the effect of skyline residuals and other non-Poisson noise sources are not included. We suspect the presence of skyline...
Figure A.1: Uncertainties on the $CaT_{F10}$ and $[Fe/H]$ as a function of signal-to-noise per Å ($S/N$). The stars show the average difference between the $CaT_{F10}$ measured directly on the SSP model spectrum and that measured on the same spectrum but with added Poisson noise. The solid line is a fit to these data points. The top abscissa shows the number counts expected if the spectra contain Poisson noise only. Our observations range from $9 \leq S/N \lesssim 60$.

Figure A.2: Variation of the average signal-to-noise per Å ($S/N$) as a function of $i$-band magnitude for the spectroscopically confirmed GCs. The shaded grey area shows the sample of 144 GCs selected for the $CaT_{F10}$ analysis.
residuals have a small effect on the uncertainties since skyline contaminated regions are excluded by the pPXF routine.

Based on the size of the uncertainties we removed spectra with raw counts less than 80 ($S/N \sim 9\AA^{-1}$) from our sample, which corresponds to roughly an $i$-band magnitude of 22.0 (see Figure A.2). This yields a maximum $CaT_{F10}$ uncertainty of 0.5 Å and a maximum $[Fe/H]$ uncertainty of roughly 0.25 dex. This left a sample of 144 spectra, sufficient for a statistical analysis.
In this section, we explore other weak spectral features that are not clearly visible in the raw GC spectra of NGC 1407 but can be measured in the fitted spectra only. While the relative strength of these weak lines may be an artefact of the fitting technique, we find that there are some interesting characteristics that may help interpret our measured $CaT_{F10}$ distribution.

The first interesting feature is the presence of the Pa12 line in a non-negligible number of our fitted spectra. An example of this is seen in Figure 2.8. It is the broad feature centred at 8751 Å and it is overlaid by a multitude of smaller features. The Pa12 line is part of the Paschen series of which 3 features overlap with the CaT features, namely the Pa13, Pa15, and Pa16 lines.

SSP model spectra do not show such Paschen lines with corresponding intermediate colours for ages $\gtrsim 2.0$ Gyrs although one must keep in mind the increased uncertainty of the models at young ages. The hollow symbols in Figure 2.12 show the GCs with measured Pa12 $\geq 1.65$ Å. Most of the data that are scattered to higher $CaT_{F10}$ index values are those with possibly large Pa12 absorption. Indeed, roughly 20 per cent of the fitted spectra at intermediate colours/metallicity have Pa12 $\geq 1.65$. The inferred average Pa12 index value for the bright blue GCs is 0.3 Å greater than that of the bright red GCs indicating that the blue GCs may contain a higher degree of Paschen contamination. Unfortunately, it is not possible with the current data to positively confirm the presence of Paschen line contamination.

We find that our fitted spectra also contain tentative evidence for the presence of several other ‘weak lines’ (i.e. Ti $\lambda 8436$ Å, Fe $\lambda 8514$ Å and Fe $\lambda 8689$ Å, see Figure 2.8). As with the Pa12 feature, these are not seen in our raw spectra but they appear...
Appendix B. Other weak spectral features

Figure B.1: Correlation between the $CaT_{F10}$ and the sum of the equivalent widths of the weak lines (Ti i $\lambda$8436Å, Fe i $\lambda$8514Å and Fe i $\lambda$8689Å), which are likely sensitive to metallicity. Filled and hollow squares correspond to Pa12 < 1.65 Å and Pa12 $\geq$ 1.65 Å, respectively, with relative sizes proportional to the signal-to-noise in the raw spectrum. The overall trend suggests that both $CaT_{F10}$ and the weak lines are tracing metallicity.

in the fitted spectra. These lines are metallicity sensitive lines and could thus serve as potential metallicity indicators provided an appropriate calibration and signal-to-noise. As a matter of fact, other groups have made use of various spectral features in the region of the CaT to measure stellar metallicities using high signal-to-noise DEIMOS spectra (e.g., Kirby et al., 2008; Shetrone et al., 2009).

Figures B.1 and B.2 show that the sum of the equivalent widths of the weak lines correlate with both $CaT_{F10}$ and colour albeit with large scatter. The tighter correlation between the weak lines and $CaT_{F10}$ (Figure B.1) suggests that both trace metallicity similarly. On the other hand, while bimodality is not readily visible in the distribution of $CaT_{F10}$, it is clear what the distribution of the sum of the weak lines is bimodal. Indeed, the KMM test concludes that a bimodal distribution is preferred over a unimodal on at the 97 per cent confidence with 65 and 35 per cent of the GCs being blue and red, respectively. This is in contrast to their colour proportion that are 40 and 60 per cent for the blue and red GCs, respectively.

When fitting our spectra we do not directly fit the small lines, which are not seen in the raw spectra. The templates themselves contain information about the relative
Figure B.2: Correlation between $(B - I)_0$ color and the sum of the equivalent widths of the three weak lines. Histograms of each variable show that both color and the equivalent widths of the weak lines are bimodal.

ratios of these lines to $CaT_{F10}$ for a given metallicity such that the distribution for the sum of the weak lines displays the expected bimodality. We speculate that while the CaT features may be saturated at high metallicity, the weak lines could still be on the growth curve and their sum a better proxy for metallicity.

We are very cautious however as these features are solely measured as a result of the template fitting method and thus the inferred bimodality could be an artefact. On the other hand, if it were an artefact it is not clear how the fitting method could conspire to create a clearer (i.e. with higher confidence) bimodality than seen in the $CaT_{F10}$ distribution.
The following publications were produced as a result of the work presented in this Thesis:

