

Probing the Epoch of Reionization

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I hereby certify that unless otherwise stated, all work presented here is my own and has not been submitted for any other degree at the University of Nottingham or any other institute of learning.

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Abstract

The first generation of stars and galaxies are formed under gravitational collapse due to perturbations seeded from quantum fluctuations in the early Universe. These sources emit ionizing radiation, carving out ionized regions of the neutral intergalactic medium. With the subsequent formation and evolution of these primordial systems, ionized regions expand and overlap such that they eventually permeate throughout the entire universe, bringing an end to the dark ages and ushering in the epoch of reionization. Despite its pivotal role, the epoch of reionization lies mostly beyond the current observational capabilities and as such, is one of the least understood periods in the history of the Universe.

The work in this thesis aims to address some of the fundamental questions regarding the epoch of reionization. Primarily investigating how current state-of-the-art facilities can push the observational frontier in the search for the first galaxies, and in the identification of low redshift analogues of the galaxies thought to play a prominent role in the reionization of the Universe.

At high redshifts, this investigation implements the unique phase space of compact, massive galaxy clusters in the search for the first galaxies. These clusters couple strong lensing potential with low levels of intracluster light, crucial for the identification of high redshift gravitationally lensed galaxies. Further, the utility of integral field observations for the identification and analysis of high redshift sources is explored. Through the design and implementation of a novel spectral extraction algorithm, sources can be successfully deblended from nearby contaminants while sufficiently increasing spectral signal-to-noise. At low redshifts, this work explores SHARDS medium-band imaging of two Frontier Field clusters for the identification of faint, low-mass dwarf galaxies, analogues of the objects believed to play a leading role in the reionization of the universe.

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Published Work

Much of the work in this thesis been previously presented in following papers:

- I Griffiths A., Conselice C.J., Alpaslan M. et al., 2018. *MUSE spectroscopy and deep observations of a unique compact JWST target, lensing cluster CLIO*. MNRAS, 475, 3, 2853–2869.
- II Griffiths A. & Conselice C.J., 2018. *AUTOSPEC: Fast Automated Spectral Extraction Software for IFU Data Cubes*. ApJ, 869, 1, 68.
- III Leisawitz D., Amatucci E., Allen L. et al., 2019. *The Origins Space Telescope* Proc. SPIE, 111150Q.

Papers I and II contain the work presented in Chapters 2 and 3 respectively. Paper III is a co-authored paper, while not presented in this thesis, contributions are a direct result of the work described in Chapter 3.

Contents

List of Figures	ix
List of Tables	xii
1 Introduction	1
1.1 Cosmological History	1
1.1.1 The Big Bang	1
1.1.2 The Early Universe	2
1.1.3 The Cosmic Microwave Background	3
1.1.4 The Dark Ages	5
1.2 Reionization	6
1.2.1 The First Stars	6
1.2.2 The First Galaxies	9
1.3 Early Galaxy Selection Techniques	11
1.3.1 Lyman Break Dropout	12
1.3.2 Lyman- α Emitters	13
1.3.3 Dusty Galaxies, GRBs and Low Redshift Analogues	14
1.4 Thesis Overview	15
2 Unique compact lensing cluster CLIO	17
2.1 Introduction	17
2.2 Target Selection	21
2.3 Observations and Data Reduction	24
2.3.1 Optical Imaging	24

2.3.2	IR Imaging	26
2.3.3	MUSE Optical Spectroscopy	27
2.3.4	Spectral Analysis	28
2.4	Results	31
2.4.1	Cluster Membership	31
2.4.2	Galaxy Populations	37
2.4.3	Cluster Properties	40
	Velocity Dispersion	40
	Cluster Centre	40
	Cluster Concentration	41
2.4.4	Luminosity Function	43
2.4.5	Intracluster light	45
2.4.6	Mass Estimation	53
	Dynamical Mass	53
	NFW Mass	53
	Stellar Hydrodynamical Mass	54
2.4.7	Preliminary Lensing Models	57
	Light-Traces-Mass modelling	58
	Weak & Strong Lensing Analysis Package	59
2.5	Summary	63
3	AutoSpec: Automated Spectral Extraction Software	68
3.1	Introduction	68
3.2	Optimal Source Identification	72
3.2.1	Cross-correlation	72
3.2.2	Isolating and deblending sources	74
3.2.3	Signal-to-noise	75
3.3	Software Methods	79
3.3.1	Initial extraction	81
3.3.2	Improving spectral quality	82
3.3.3	Using the software	83

	Output	85
3.4	Alternative Uses	86
3.5	Summary	86
4	Emission line galaxy selection and $H\alpha$ emitters	89
4.1	Introduction	89
4.2	Observations and data reduction	93
4.2.1	Data Sources	94
	Medium-band observational data	94
	Ancillary observations and catalogues	95
4.2.2	Photometric calibration	96
	Total Flux Measurements	98
	Flux Corrections	99
	Geometric effects	99
4.2.3	Updated Photometric Redshifts and Stellar Population Parameters	100
	Photometric Redshifts	101
	Stellar Population Parameters	102
4.3	Emission Line Galaxy Selection	103
4.3.1	Broad-band Continuum	104
4.3.2	Selection	104
4.3.3	$H\alpha$ Emitters	107
	Removal of [NII] line contamination	112
	Extinction correction	112
	Star formation rates	113
4.3.4	Structure and Morphologies	115
4.4	Results	116
4.4.1	Emission line candidates	116
4.4.2	$H\alpha$ main-sequence	118
4.4.3	$H\alpha$ equivalent width vs stellar mass	119
4.4.4	Bursty star formation	120

Comparison of $H\alpha$ and UV derived SFRs	122
Specific star formation rates	123
4.4.5 Structure and Sizes	126
4.5 Discussion	128
4.6 Conclusions	134
5 Escape Fractions of Merging Galaxies	137
5.1 Introduction	137
5.2 Observations and Data Reduction	143
5.2.1 Lensing Magnification	143
5.2.2 Selection of Line-Emitters	144
Selected emission lines	144
5.3 Results	146
5.3.1 LyC Escape Fraction Formalism	146
5.3.2 Individual limits	147
5.3.3 Stacked limits	151
5.3.4 Merger Identification	154
5.4 Discussion	162
5.4.1 Implications	162
5.4.2 Role of Merging	164
5.5 Summary	166
6 Thesis Summary	169
6.1 Compact lensing clusters	169
6.2 Optimised spectral extraction	170
6.3 Emission line galaxies and bursty star formation	171
6.4 Escape fractions	172
Bibliography	172

List of Figures

1.1	Planck 2018 CMB temperature anisotropy map	4
1.2	Radiative transfer simulation of the epoch of reionization	7
2.1	Dynamical masses as a function of concentration for GAMA groups.	23
2.2	Examples of cluster member, and background galaxy spectra extracted from the MUSE datacube	30
2.3	Spectroscopic redshift distribution of galaxies within the observed MUSE field.	32
2.4	Spatial distribution of spectroscopically identified galaxies overlaid on the FORS2 r -band image.	35
2.5	3D distribution of cluster members.	36
2.6	Comparison of spectroscopic redshifts to DEmP photometric redshifts from the first HSC public data release.	38
2.7	Colour-Magnitude relations of CLIO members, foreground and background galaxies.	39
2.8	The r -band luminosity function of cluster galaxies within the CLIO cluster.	46
2.9	Visual representation of the full GALFIT modelling procedure for ICL estimation.	48
2.10	Illustration of GALFIT modelling procedure.	49
2.11	ICL fraction as a function of cluster redshift with a comparison to other studies.	51
2.12	Radial surface brightness profile of the ICL and total cluster light. .	52
2.13	Radial mass, velocity dispersion and number density profiles of cluster members.	56
2.14	Positions of arclet constraints used in WSLAP+ modelling.	60

2.15	Preliminary lensing models for the CLIO cluster showing critical curves at $z = 1.2, 2.2$ and 6.	62
2.16	Enclosed mass profiles derived from both LTM, and WSLAP+ lensing models for the CLIO cluster.	64
3.1	Illustration showing the effectiveness of continuum subtraction for the isolation of sources from nearby contamination.	76
3.2	Example of improvements in the signal-to-noise of a spectrum using our cross-correlation strength maps.	78
3.3	Signal-to-noise measurements for a variety of objects and extraction methods.	80
3.4	Example galaxy spectra extracted via the various methods available within AUTOSPEC.	84
3.5	Examples demonstrating the power of our source identification methods with alternative data types.	87
4.1	Transmission curves of the SHARDS and HST filters used for the selection of emission line galaxies	95
4.2	Observational field-of-view comparison of SHARDS data	97
4.3	Photometric redshift and stellar population parameter comparison .	103
4.4	Colour-colour plot showing broad-band continuum magnitude corrections for all objects.	105
4.5	Medium-band excess as a function of F913W medium-band magnitude	108
4.6	Redshift and stellar mass comparison of emission line selected galaxy candidates.	109
4.7	$H\alpha$ candidate locations within the A0370 cluster field	111
4.8	The main-sequence of our $z \sim 0.4$ line emitters with $H\alpha$ -derived star formation rates	119
4.9	Relation between $H\alpha$ rest-frame EW and sSFR	121
4.10	Comparison of the $H\alpha$ and UV SFRs	124
4.11	Specific star formation rates derived from $H\alpha$ and UV luminosities .	127
4.12	The size mass relation for our sample of galaxies	129
4.13	The relation between Sersic index, n and the stellar mass	130
4.14	Diagram showing the concentration vs. asymmetry diagram for our sample	131

4.15	Mosaic of the 38 sources with structural and morphology measurements	132
5.1	Mass distribution of LyC emitter candidates	144
5.2	Redshift distribution of LyC emitter candidates	145
5.3	Average IGM transmission of UV light for an example galaxy at $z \approx 3$	150
5.4	Example postage stamp cut outs and stacked images for HST UVIS F275W band objects in the A0370 cluster	152
5.5	Example postage stamp cut outs and stacked images for HST UVIS F336W band objects in the A0370 cluster	153
5.6	Postage stamps and SEDs of the two galaxies with LyC flux mea- surements $> 2\sigma$	155
5.7	Relative escape fractions as a function of redshift, M_{uv} and demag- nified stellar mass	158
5.8	Mosaic with 40 out of 42 sources with valid Asymmetry measure- ments ordered by ID	161
5.9	Asymmetry as a function of signal-to-noise for candidate LyC emitters	166

List of Tables

2.1	Summary of redshift determinations and quality flags assigned to spectra extracted from the MUSE datacube.	31
2.2	Cluster member spectroscopic redshift catalogue.	32
2.3	Background object spectroscopic redshift catalogue.	33
2.4	Table of central positions and redshifts for arclet constraints used in the WSLAP+ modelling.	61
4.1	SHARDS Filter details.	95
4.2	Detection filter redshift range and cluster candidate counts of H α emitters.	112
4.3	Summary of the structure and morphology measurements of selected sample	117
5.1	Number counts and redshift range for initial Lyman continuum emitting candidates.	145
5.2	Summary of individual escape fraction of emission line selected galaxies from the M1149 cluster	156
5.3	Summary of individual escape fraction of emission line selected galaxies from the A0370 cluster	157
5.4	Summary of escape fractions for stacked images	159

Chapter 1

Introduction

1.1 Cosmological History

Einstein's theory of general relativity combines special relativity with Newton's laws of gravitation and forms the basis of the standard cosmological model of the Universe (Einstein, 1916). Characterised by Einstein's field equations, general relativity describes gravity as a property of spacetime and its geometry, determined by the distribution of matter and energy, which in turn describes the acceleration of matter, and thus the evolution of the Universe. Under the assumption of the cosmological principle (the Universe is homogeneous and isotropic when viewed on large enough scales), the Friedmann-Lemaître-Robertson-Walker (FLRW; e.g. Friedmann, 1922; Lemaître, 1931; Robertson, 1935; Walker, 1937) metric tensor provides an exact solution to Einstein's field equations.

1.1.1 The Big Bang

Solutions to the FLRW metric imply that the Universe grew rapidly from a hot, dense state immediately following a singularity. While physical understanding of the singularity likely requires quantum theories of gravity, solutions to the FLRW metric underpin the leading cosmological standard model of today, the Big Bang

Theory.

Today, this rapid period of expansion is referred to as inflation. Coined by Alan Guth (1981) while investigating the magnetic monopole problem (stable magnetic monopoles predicted from Big Bang cosmology have not been observed), the inflationary epoch likely lasted from around 10^{-36} - 10^{-32} seconds after the Singularity (Big Bang). This almost exponential expansion of the Universe is thought to be driven by a scalar field produced at the phase transition which separated the strong and electroweak forces. Observational clues of inflation are ingrained into the Cosmic Microwave Background (CMB), however the “smoking gun” of inflationary gravitational wave signatures have yet to be detected. Cosmic inflation helps to explain observed properties of the Universe such as the large scale structure, it also provides answers to long standing issues with the Big Bang theory, such as the Horizon (widely separated regions of the observable universe that are not in causal contact, but are thermally equilibrated) and Flatness problems (the geometry of the universe is observed to be close to flat, however as curvature grows with time extreme fine-tuning or initial conditions is required).

1.1.2 The Early Universe

At the end of inflation, the Universe consists of a hot plasma produced as the inflationary field decays into quarks, anti-quarks and gluons. At 10^{-12} seconds after the Big Bang, particle energies are low enough for the Quark-Gluon plasma to begin to coalesce into hadron/anti-hadron pairs. Initially, these particles annihilate each other producing high energy photons; however as the Universe cools further, new pairs are no longer produced and small asymmetries result in the destruction of most anti-hadrons. By the end of this phase (roughly one second after the Big Bang), the temperature of the Universe has cooled to $\sim 10^{10}$ K where thermal equilibrium between neutrons, protons and electrons is no longer maintained by

the weak nuclear force, and neutrinos decouple from baryonic matter.

With the annihilation of most hadron/anti-hadron pairs, leptons came to dominate the mass-energy of the Universe. Following a similar evolutionary path to hadrons, lepton/anti-lepton pairs annihilate each other, producing high energy photons until the Universe cools sufficiently (~ 10 s) such that no new pairs are created and a small fraction of residual leptons remain.

At the end of the lepton epoch, high energy photons left over from particle/anti-particle annihilation's dominate (with a small amount in relativistic particles). With continued expansion and cooling of the Universe, temperatures drop such that protons and neutrons can combine into hydrogen and helium-4 nuclei. Within minutes, the temperature becomes low enough such that nucleosynthesis can occur, and small amounts of light elements such as deuterium, helium-3 and lithium-7 are formed (e.g. Lepp & Shull, 1984; Palla et al., 1995; Kusakabe et al., 2014). Some heavier elements are also produced at this time but are unstable and quickly decay.

After around 47,000 years, the energy density of matter exceeds that of radiation and the vacuum such that the Jeans length decreases. Perturbations seeded from quantum fluctuations in the early Universe (before inflation) are then free to grow through gravitational collapse to become the initial stages of structure formation. However, it is not baryons that play a leading role in the formation of structure, but dark matter, which is unimpeded by radiation pressure and can collapse without the loss of energy into large diffuse haloes. As a consequence, these dark matter driven gravitational overdensities accelerate the collapse of ordinary matter into what will eventually become the first stars and galaxies.

1.1.3 The Cosmic Microwave Background

Towards the end of nucleosynthesis, the Universe consists of a hot ionized baryonic plasma, such that the mean free path of photons was short and the Universe is

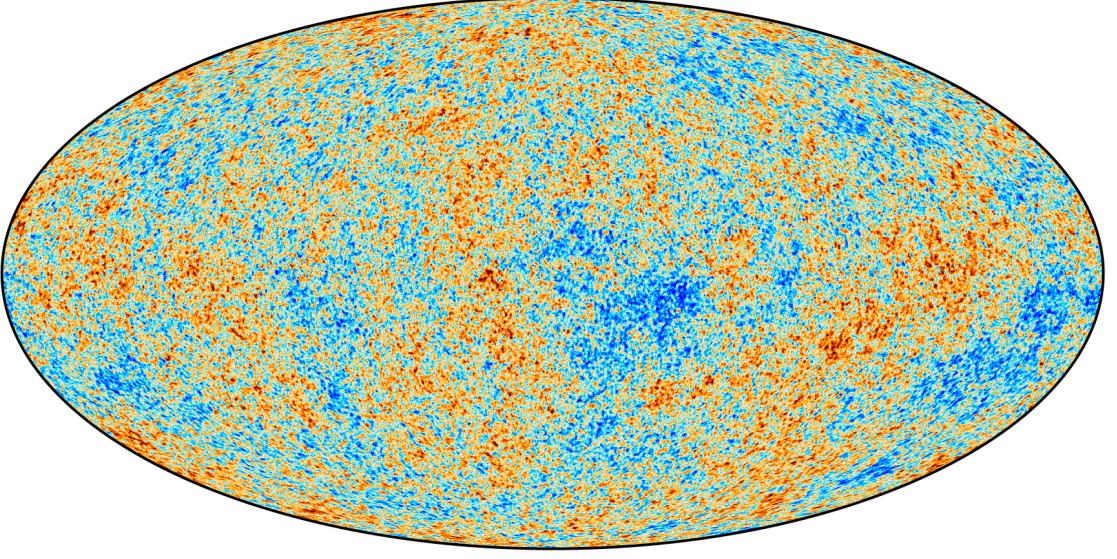


Figure 1.1: The 2018 Planck map of the temperature anisotropies of the cosmic microwave background (Planck Collaboration et al., 2018a). Temperature fluctuations on the scale of 10^{-5} are ingrained due to matter density perturbations at the time of recombination which are the seeds of structure formation.

opaque to electromagnetic radiation due to Thomson scattering by free electrons. However, when the Universe is around 370,000 years old ($z = 1100$) it has cooled to a point where it becomes energetically favourable for electrons to bind with the hydrogen nuclei to form neutral hydrogen atoms. These atoms generally form in a high energy state and quickly transition through the emission of either a photon pair (from the $2s$ state); or a Lyman- α photon (from the $2p$ state), however the latter is usually reabsorbed by another neutral hydrogen atom (e.g. Peebles, 1968; Zeldovich et al., 1968). While this is the first time in the history of the Universe that electrons have become bound to atomic nuclei, for historical reasons this process is named recombination.

By the end of recombination, the free electron density has dropped significantly due to the formation of neutral hydrogen. As a result, the mean free path of photons becomes equal to the horizon size, and, for the first time in its history, the Universe becomes transparent to electromagnetic radiation which does not

have the required energies to excite or ionise the neutral hydrogen. This process of photon decoupling happens when the Universe is at a temperature of around 3000 K and results in an effective boundary between the opaque and transparent universe, which we call the surface of last scattering. This black body radiation permeates throughout the entire universe, travelling unimpeded such that it can still be observed today in the cosmic microwave background (CMB).

The CMB was accidentally discovered by Arno Penzias and Robert Wilson (Penzias & Wilson, 1965) and provides the most substantial evidence in support of the Big Bang model. Observed to be roughly consistent with a black body spectrum at 2.725 K, CMB photons experience a temperature drop since the time of last scattering due to the redshifting effects of the expansion of the Universe. While the CMB is extremely isotropic, temperature fluctuations on the scale of 10^{-5} are ingrained due to matter density perturbations at the time of recombination, and are the seeds of structure formation. Precise measurements of the CMB and its anisotropies have helped to constrain the Lambda Cold Dark Matter (Λ CDM) model and provided some of the most accurate measurements of cosmological parameters such as the age of the Universe, the Hubble constant and matter energy densities (e.g. Planck Collaboration et al., 2018b).

1.1.4 The Dark Ages

The end of the recombination epoch marks the beginning of the cosmic dark ages. As the Universe cools to around 60 K over the following 150 million years, there are two dominant sources of photons; those released during recombination/decoupling and the 21cm emission of neutral hydrogen (although gas dynamics could lead to heating and the the release of Lyman-alpha photons). The distribution of this atomic gas is thought to remain relatively homogeneous until the formation of the first stars and galaxies, as only small fractions form the first molecules such as H_2

and LiH. The cosmic dark ages are considered to be a rich source of information in which observational data would put tighter constraints on cosmological parameters (Cooray et al., 2008; Mao et al., 2008) and provide insight into the birth of protogalaxies and the physics of the intergalactic medium (IGM). While these observations currently remain out of reach, substantial effort will be made with upcoming projects such as the Low Frequency Array (LOFAR; Zaroubi & Silk, 2005) and the Square Kilometre Array (SKA; Mellema et al., 2013).

1.2 Reionization

The first snapshot of cosmic history is provided by the CMB when the Universe was less than 400,000 years old (e.g. Spergel et al., 2003). This marks the beginning of the cosmic dark ages when the Universe was filled with almost isotropic, neutral hydrogen. Our next clear picture is provided by deep Hubble Space Telescope (HST) observations almost a billion years later, revealing a Universe with an abundance of star forming galaxies and a highly ionized IGM. Thus, one of the most important frontiers in observational astronomy is to form an understanding of how this transition occurred and what roles the first stars, galaxies and black holes played.

1.2.1 The First Stars

The formation of the first stars not only brings an end to the dark ages, but the transition from a relatively simple homogeneous Universe to that of a highly complex, structured one. In order for the atomic gas to collapse into the potential wells of existing dark matter halos and form stars, the Jeans mass of the gas must be below that of the halo mass. This happens at temperatures $\lesssim 10^4$ K where gas pressure no longer prevents collapse. Additionally, radiative cooling is needed for the gas to reach densities required for star formation, and in the absence of heavy

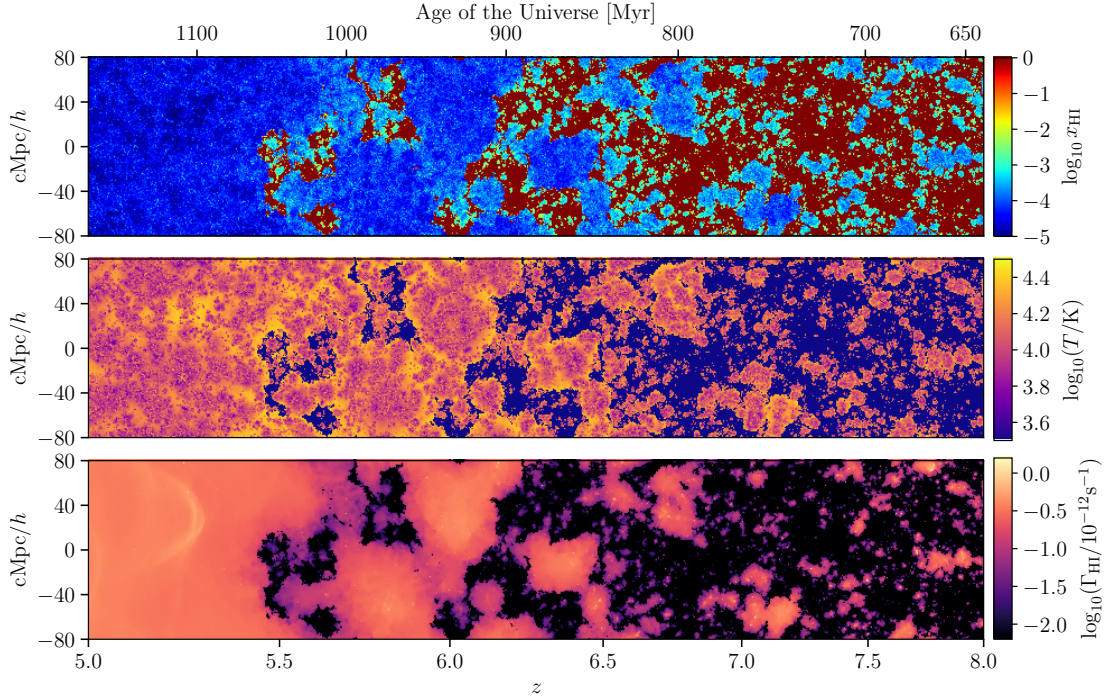


Figure 1.2: Radiative transfer simulation of the epoch of reionization, based on the Sherwood simulation suite. Top panel shows the evolution of the neutral hydrogen fraction. The middle panel shows the temperature of the Intergalactic Medium and the hydrogen photo-ionization rate is shown on the bottom panel. Figure obtained from: Kulkarni et al. (2019).

elements this can only be accomplished by H_2 cooling.

From estimations of the cooling timescales and ΛCDM models, it is thought that the first stars formed in dark matter minihalos of mass $\sim 10^6 M_\odot$ at redshifts $z \sim 20 - 30$ (e.g. Couchman & Rees, 1986; Tegmark et al., 1997; Yoshida et al., 2003). As the primordial gas had not yet been enriched by supernovae, the first generation of stars constitute the zero metallicity Population III (Pop III) class. Early numerical simulations predict that the Pop III generation of stars were predominantly high mass (~ 100 's $M_\odot$) and had relatively short lifetimes compared to the stars we see in the Universe today (Bromm et al., 1999; Nakamura & Umemura, 2001). More recent, higher resolution simulations have shown that the Pop III initial mass function (IMF) may be broader than initially thought, extending down to solar mass, particularly if stars form in binaries or large groups

due to fragmentation of the primordial gas (e.g. Clark et al., 2011; Hosokawa et al., 2016; Stacy et al., 2016). Further, the possibility of this extension to the lower masses means that some Pop III stars could in fact be long-lived, and may even be found in the local Universe (e.g. Starkenburg et al., 2017; Wolf et al., 2018). To date, no Pop III stars have been observed despite many focused searches; however this may change in upcoming years as their detection is one of the main science goals of the upcoming James Webb Space Telescope (JWST; Rydberg et al., 2013).

This first generation of stars are thought to play a leading role in the subsequent evolution of the Universe and galaxy formation. Primarily, these massive stars produced vast amounts of high energy ultraviolet (UV) photons which can ionize the surrounding neutral hydrogen gas, forming ionized H II bubbles. Observations of the CMB from the Wilkinson Microwave Anisotropy Probe (WMAP) and Planck (e.g. Sokasian et al., 2004; Miranda et al., 2017) have put constraints on the total ionizing photon budget of the first stars, showing a non-negligible contribution to early reionization ($15 \lesssim z \lesssim 20$) of up to 20%.

While high energy photons (>13.6 eV) produced by the first stars are absorbed by the surrounding neutral gas, photons with energies between 11.2 and 13.6 eV (Lyman-Werner radiation) are able to traverse greater distances through the atomic medium. These photons can photodissociate H_2 (Draine & Bertoldi, 1996), resulting in a suppression of the cooling rate and the ability to form further stars. Pop III stars are also thought to self-regulate through metal enrichment, where supernovae eject heavy elements which pollute the atomic medium and enhance the gas cooling efficiency, resulting in a reduction of the Jeans mass and a shift in star formation to lower mass stellar populations (e.g. Mackey et al., 2003; Yoshida et al., 2004). Stars in the mass range of $140M_\odot \lesssim M_* \lesssim 260M_\odot$ could have played an important role in this process as their lives end in a pair-instability supernovae (PISN), resulting in the complete destruction of the progenitor star such that heavy

elements are readily dispersed into the atomic medium (Fryer et al., 2001; Heger et al., 2003).

The importance of these feedback mechanisms is still up for debate (Ricotti et al., 2002a,b; Machacek et al., 2003; Yoshida et al., 2003), but recent results suggest that they are needed to match constraints set by Planck observations (e.g. Visbal et al., 2015; Miranda et al., 2017). This would imply that this first generation of stars were self-destructive and short-lived, as their own influence destroys the conditions that made their formation possible.

1.2.2 The First Galaxies

The standard Λ CDM cosmological model predicts a hierarchical mode of structure formation in which large dark matter halos are built up through the merging and accretion of smaller halos (e.g. Blumenthal et al., 1984; Springel et al., 2005). Therefore the formation of the first galaxies must be intrinsically linked to their progenitor systems and the feedback mechanisms at play within these dark matter minihalos (Bromm et al., 2009). As the radiative effects of Pop III stars begin to build up ionized H II regions, commencing the extended process of reionization, supernovae enrich the IGM with heavy elements while their blastwaves impart heat and momentum to the surroundings. Both of which affect subsequent star formation and the assembly of the first galaxies.

With a current lack of observational evidence, the definition of what constitutes the first galaxies needs to be attained from a theoretical standpoint. While there is much debate on this topic, leading theories agree on the general stipulation that a galaxy must be situated within a dark matter halo large enough to host a long-lived stellar system. This could require the halo's gravitational potential to be deep enough that it is able to retain $T > 10^4$ K gas heated by stellar radiation (Mesinger & Dijkstra, 2008; Mesinger et al., 2009). Some theories go further to

also allow for the preservation of supernovae accelerated gas. The specifics however hinge on the IMF of Pop III stars and the nature of their life-cycle and feedback mechanisms.

Some theories propose that the dark matter minihalos ($\sim 10^6 M_\odot$) responsible for the formation of Pop III stars could also be the hosts for the first galaxies (Ricotti et al., 2002a). This relies on an assumption that the Pop III IMF is similar to that of the local value as suggested by recent high-resolution numerical simulations (Stacy & Bromm, 2013; Hirano et al., 2014; Stacy et al., 2016), in which the distribution peaks at low masses of $< 1M_\odot$ such that negative feedback effects are not strong enough to disrupt subsequent star formation. However, if this is not the case and the first stars belong to a predominantly massive population (Omukai & Palla, 2003; Bromm et al., 2009), feedback would likely leave these minihalos devoid of the gas required for galaxy formation. Some theoretical predictions resolve this issues by proposing that a slightly larger minihalo ($10^7 M_\odot$) combined with a mostly neutral integral gas fraction could lead to the confinement of feedback pressure waves and a self-enrichment of the halo (Kitayama & Yoshida, 2005).

The most commonly accepted scenario for the formation of the first galaxies constitutes a larger dark matter host halo of mass $\sim 10^8 M_\odot$. These systems, thought to form at around $z \sim 10$ through hierarchical assembly, could retain and revirialise the gas accelerated via supernovae feedback, thus allowing for ongoing star formation (Wise & Abel, 2008; Greif et al., 2010). These halos are thought to be above the critical temperature for hydrogen cooling (and Pop III star formation), but chemical enrichment of the interstellar medium (ISM) of progenitor systems enables the formation of second generation (Pop II) stars (Oh & Haiman, 2002). This stellar generation likely included the stars of low enough mass that they may have survived to the present day.

Over the next billion years, these primordial dwarf galaxies are thought to

rapidly grow in mass through halo mergers and the accretion of surrounding cold gas. The Lyman continuum radiation (photons with energies above the Lyman limit of $912\text{\AA}$) they produce continues to reionize the IGM, forming ionized bubbles surrounding these matter overdensities until they eventually overlap and the Universe is fully ionized, marking the end of reionization. However, as quasars and Pop III stars also produce ionizing UV photons; the exact contribution dwarf galaxies play in reionization remains unclear.

From an observational perspective, the definition of the first galaxy is ever evolving and defined by the highest redshift system observed. At the time of writing this is the spectroscopically confirmed $z = 11.09$ galaxy, GN-z11 (Oesch et al., 2016). Formed just 400 million years after the Big Bang, GN-z11 is found to be a fraction of the size of the Milky Way and contains only $\sim 1\%$ of the mass. Situated at the observational frontier of HST, this galaxy provides our earliest insight into the composition of early galaxies. Yet, even at $z \sim 11$, the spectroscopic signatures of Pop III stars (such as the He II recombination lines) and the low metallicities expected to constitute the very first galaxies is yet to be observed.

1.3 Early Galaxy Selection Techniques

In the last decade the search for the first galaxies has pushed back the observational frontier to redshift $z \approx 11$. Much progress has been made thanks to deep imaging campaigns with HST which has yielded thousands of galaxies at $z > 6$. Similarly, Lyman- α ($\text{Ly}\alpha$) surveys, gamma ray burst (GRB) afterglow spectra and low redshift analogues are providing insight into the nature of these galaxies, while CMB observations by Planck are further constraining the electron scattering optical depth and reionization timescales. In the coming years, new facilities such as JWST and SKA will push the observational frontier back even further. Until that time however, it is important to push current technology in an effort to explore this

epoch of the Universe's history.

1.3.1 Lyman Break Dropout

In the absence of sufficient dust in the early Universe to attenuate light, massive stars within these galaxies contribute to strong UV continuum emission. However, high energy radiation beyond the Lyman limit ($\lambda_{rest} = 912\text{\AA}$) is almost entirely absorbed by neutral hydrogen gas in the interstellar medium (ISM; the gas and dust between stars within a galaxy) and intergalactic medium (IGM; hot, X-ray emitting gas that permeates the space between galaxies), resulting in a sharp break in the emerging spectrum that is bright at wavelengths above the Lyman limit, but extremely faint or zero below. This observable break, or dropout, can be used in combination with multi-band imaging to estimate the position of the Lyman limit and thus, the redshift of a galaxy. However, care must be taken as this dropout selection can be contaminated by the $4000\text{\AA}$ /Balmer breaks and dust.

Substantial breakthroughs in dropout selection came with the installation of the Advanced Camera for Surveys (ACS) and the Wide Field Camera 3 (WFC3) on HST, allowing for the identification of sources up to $z \sim 6$ and $z \sim 8$ respectively through improved sensitivity and additional filters. At these redshifts, wide area ground based IR campaigns such as the Ultra Deep Survey with the VISTA telescope (UltraVISTA) have helped provide constraints on the bright end of the luminosity function (e.g. Bowler et al., 2014, 2015). Beyond these redshifts, Spitzer Infrared Array Camera (IRAC; Fazio et al., 2004) imaging has pushed limits out to $z = 11$ by combining its infra-red sensitivity with the strong gravitational lensing effects of galaxy clusters such as those within the Hubble Frontier Fields (Lotz et al., 2017).

1.3.2 Lyman- α Emitters

Originally proposed as a means of identifying high redshift sources by Partridge & Peebles (1967), the Ly α emission line selection technique has been successful in the identification of numerous early galaxies. The Ly α emission line (1216Å) is the most intrinsically luminous spectral feature of star-forming galaxies produced via the recombination of ionized hydrogen in the ISM/IGM. Thus, Ly α emitters (LAEs) are able to not only provide large samples of galaxies which can be used to measure the high-redshift luminosity function, but also the details of the evolution and reionization of the IGM through line profiles and luminosities. The main benefit of Ly α surveys is that they are emission-line based, enabling the detection of much fainter sources than other methods (e.g. Lyman-break), and even objects that are undetected in deep HST imaging (e.g. Karman et al., 2017).

At redshifts $z = 5 - 7$, the Lyman- α line is shifted into a dense region of OH skylines which dominate the sky background. In order to avoid contamination by these atmospheric lines, narrow-band filters can be implemented to probe empty regions within the noise (at redshifts 4.5, 4.8, 5.7, 6.5, 7.7, and 9.0) such that even galaxies with faint continuum emission can be detected. Due to the narrow bandpass of these filters, candidates are generally required to be 1 magnitude brighter than in the adjacent broadband filter, corresponding to a Lyman- α equivalent width of $\sim 20\text{\AA}$.

This selection technique first saw success at the end of the 1990s with the detection of multiple galaxies at $z > 5$ (Dey et al., 1998; Hu et al., 1998). Only a few years later, the first $z > 6$ LAE was discovered, aided by the strong gravitation lensing capabilities of the Abell 370 galaxy cluster (Hu et al., 2002). Many early searches involved wide area narrow-band surveys such as the Large-Area Lyman- α survey (LALA; Rhoads et al., 2000) and the observing campaigns of the Suprime-Cam (e.g. Ajiki et al., 2004; Ouchi et al., 2008). Further progress was made through

the combination of multiple narrow- and medium-band filters in which samples of thousands of LAEs from $z \sim 2$ to $z \sim 7$ have been detected (Sobral et al., 2018; Calhau et al., 2020; Santos et al., 2020). Today, the most recent innovation comes with state-of-the-art wide-area integral field units (IFUs) such as the Multi Unit Spectroscopic Explorer (MUSE; Bacon et al., 2010). These IFU observations allow for the simultaneous detection and spectroscopic confirmation of multiple high redshift LAEs by searching for emission lines within the 3D data (Bacon et al., 2017).

1.3.3 Dusty Galaxies, GRBs and Low Redshift Analogues

While the Lyman break and LAE selection techniques have yielded a large sample of high redshift galaxies, they provide a biased view of the early Universe, and typically do not reach low enough luminosities to probe the faint end slope of the mass function. Thus, complementary techniques should be used. One such method is the search for dusty star-forming galaxies (DSFGs) that are frequently missed in UV rest-frame selection. These galaxies form stars at incredibly high rates (100s - 1,000s $M_{\odot} \text{ yr}^{-1}$) and are the most extreme stellar nurseries in the Universe, thought to contribute up to 90% of early ($z > 4$) star-formation rate density (Rowan-Robinson et al., 2016). DSFGs are currently extremely difficult to detect and only a handful of high redshift objects have been found to date. However this is set to change with upcoming observational facilities such as JWST with its infrared capabilities.

Gamma-ray bursts (GRBs) also provide a useful method for studying the epoch of reionization as their extreme luminosities enable the detection and spectroscopic confirmation of high redshift sources independent of the $\text{Ly}\alpha$ emission line. As GRBs are fuelled by individual massive stellar systems, they probe the entire luminosity function of galaxies, including those that would otherwise be too faint

to be detected by other methods. Another benefit of GRBs is that their afterglow is intrinsically featureless, providing a means to study the column densities and chemical enrichment of the ISM (e.g. Fynbo et al., 2009; Berger et al., 2014), as well as the ionization state of the IGM (e.g. Miralda-Escudé, 1998; McQuinn et al., 2008).

An alternative method of investigating the epoch of reionization is to look to low redshift analogues of the sources thought to play a key role. While these galaxies should be easier to study than their counterparts at high redshift, sample sizes still remain relatively small. Galaxies such as those in the Lyman Alpha Reference Sample (LARS; Östlin et al., 2014; Hayes et al., 2014), Lyman Break Analog Sample (Heckman et al., 2005) and Green Peas (Cardamone et al., 2009) are currently found to be more massive than those expected to be responsible for reionization. However, surveys such as Calibrating Lyman- α with H α (CALYMHA) are revealing sources at $z \sim 2$ with properties much closer to those expected of the low redshift analogues (Matthee et al., 2016; Sobral et al., 2017). On the other hand, the properties of local blue compact dwarf galaxies have been shown to be promising analogues of the dwarf galaxies thought to significantly contribute to the reionization of the Universe (see review; Kunth & Östlin, 2000).

1.4 Thesis Overview

The work in this thesis aims to address some of the fundamental questions regarding the epoch of reionization. Primarily, this investigates sources at the observational frontier of astronomy, as well as low redshift analogues of the galaxies thought to play a prominent role in the reionization of the Universe.

In Chapter 2, I explore a new type of lensing cluster in the search for the first galaxies. The main objective is to study the unique phase space of compact,

massive clusters in the search for gravitationally lensed galaxies at the epoch of reionization.

Chapter 3 presents the AutoSpec software, designed for the optimal extraction of one dimensional spectra from IFU datacubes. Through an increase in spectral signal-to-noise and detailed removal of contamination, I aim to provide a technique which will enable accurate redshift estimates and more detailed spectroscopic analysis of faint, high-redshift objects.

In Chapter 4 I select emission line galaxies in two of the Hubble Frontier Fields using narrow-band selection techniques, and investigate the bursty star formation histories of faint $H\alpha$ emitters. This work is continued in Chapter 5, where I explore the escape fractions of low-mass dwarf galaxies, low redshift analogues of those objects thought to play a leading role in reionization.

Finally, Chapter 6 provides a summary of this thesis. Throughout this thesis a Λ cold dark matter cosmological model is adopted with $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$ and $H = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. All magnitudes are given in the AB system (Oke, 1974).

Chapter 2

Unique compact lensing cluster CLIO

In this Chapter we investigate the compact lensing cluster CLIO in order to determine its utility for future JWST observations in the search for high redshift galaxies. We discuss how the cluster was selected for VLT MUSE/FORS2 and Spitzer follow up observations based on its high mass and dark matter halo concentration. MUSE spectroscopic data is used in combination with dual band FORS2 imaging to identify cluster members and background galaxies out to $z = 6.5$. Initial estimates of cluster mass and concentration are refined, we estimate the intracluster light fraction through galaxy profile fitting and build preliminary lensing models. This work is published in full in Griffiths et al. (2018).

2.1 Introduction

Beginning their formation with the gravitation collapse of overdensities in the initial primordial density field, galaxy clusters are the largest gravitationally bound objects in the Universe. Clusters can serve as unique laboratories for the study of both astrophysics and cosmology. Since they were first hinted at in the clustering of nebula seen by the Herschels, galaxy clusters have led to a number of

groundbreaking scientific discoveries. For example, in 1933, Zwicky demonstrated the need for a dark matter component by investigating the mass of the Coma cluster (Zwicky, 1933). In terms of galaxy evolution, in the early 1950s Spitzer and Baade first studied cluster environments to reveal the collisional stripping of interstellar matter through galaxy interactions (Spitzer & Baade, 1951).

In recent decades, advances in observational capabilities have provided a detailed insight into the structure of galaxy clusters and their dynamical evolution. This improved understanding of cluster physics has provided a tool to investigate large-scale structure, refine cosmological models, and probe the early Universe through gravitational lensing (e.g., Zheng et al., 2012; Coe et al., 2015; Dye et al., 2015). With the advent of new observational facilities such as JWST, Euclid and LSST in the next decade, clusters are bound to become an even more important environment in which to learn new astrophysics about the early universe as well as the first stars and galaxies. JWST observations of lensing clusters will probe significantly deeper than current observational capabilities in the search for high redshift galaxies and population III stars, while Euclid and LSST will use galaxy clusters to complement studies into the accelerated expansion of the Universe, and the nature of dark energy and dark matter.

A prime example of this is through the exploitation of massive galaxy clusters as gravitational lenses. This has proved to be a valuable method for studying the early Universe. Typical methods such as the Lyman break technique (e.g., Steidel et al., 1996; Giavalisco et al., 2004) often rely on the use of deep blank fields, in which early galaxy populations have been characterised through UV colours, stellar masses and ages (Duncan et al., 2014). The magnification of faint background sources by gravitational lenses provides a complementary method to detect even fainter galaxies over a wide range of redshifts (e.g., Brammer et al., 2012; Alavi et al., 2014). In this vein, large, dedicated cluster surveys such as the Hubble Frontier Fields (HFF;

Lotz et al., 2014; Koekemoer et al., 2014) and the Cluster Lensing And Supernova survey with Hubble (CLASH; Postman et al., 2012) have targeted a number of massive clusters for use in gravitational lensing studies.

Detailed observations and programs such as the HFF and CLASH have led to significant improvements in our ability to successfully model cluster mass distributions. Through the identification of lensed arcs, and multiply-imaged background sources, it is possible to refine mass models such that clusters can be used as gravitational telescopes to locate, and study high redshift objects. These density maps are constructed as a combination of the cluster population, and an inferred dark matter distribution (e.g., Frye & Broadhurst, 1998; Zitrin et al., 2012a; Jauzac et al., 2015; Grillo et al., 2015; Kawamata et al., 2016).

By far the most common type of cluster in the distant universe that has been studied in detail are the most massive ones ($> 10^{15}$), such as those in the Frontier Fields and CLASH. There are however good reasons for wanting to investigate other types of clusters. In particular, compact (highly concentrated mass distribution) but massive clusters provide a potentially powerful approach for obtaining new and complementary information about dark matter distributions, as well as an alternative approach for studying gravitationally lensed galaxies. The reasons for this are that a compact cluster will have a potentially different structure than a typical large massive cluster, providing a new avenue to study dark matter distributions. Furthermore, a compact massive cluster will lens background galaxies through a lower amount of intracluster light, making them ideal targets for finding the most distant galaxies in the universe.

Here, we present the first results obtained from dedicated observations of such a compact galaxy cluster, which we name the CLIO cluster after the Greek muse of history (see Section 2.2 for more details). CLIO was identified within the Galaxy and Mass Assembly (GAMA; Driver et al., 2011; Liske et al., 2015) survey at an

intermediate redshift of $z = 0.42$. We use dual band FORS2 and IRAC imaging in conjunction with spectroscopic MUSE data in order to refine the properties of this cluster, building upon the initial measurements from the GAMA data. We measure spectroscopic redshifts to identify cluster members, and aim to identify multiply-imaged sources in order to construct an improved mass distribution of the cluster. Combining spectroscopy with imaging data also enables us to measure member luminosities and masses in order to estimate the relative baryon mass fraction of the cluster.

As mentioned, high mass clusters which provide sufficient curvature in spacetime to be beneficial for gravitational lensing, also tend to contain large amounts of diffuse intracluster light (ICL), which can prove to be a hindrance, as while this component can be subtracted off it leaves high levels of residual noise. Therefore minimal ICL contamination is essential when studying cluster lenses where such stray light components can impede the detection of faint lensed sources in the cluster centre, which would otherwise provide crucial constraints on mass models. Recent studies have found ICL fractions at medium redshifts ($0.3 < z < 0.6$) of $\sim 10\text{--}20\%$, around half of the local value ($\sim 40\%$; Gonzalez et al., 2013), suggesting that the ICL is still being produced at $z < 1$ (Morishita et al., 2017; Jiménez-Teja & Dupke, 2016). Thus, in this study we investigate the ICL fraction in regards to utilising the CLIO cluster as a potential gravitational lens.

This study is part of preliminary work towards our James Webb Space Telescope (JWST) GTO program 1176 (PI Windhorst), ‘Webb Medium-Deep Field’ survey (WMDF). This program will look at a combination of lensing clusters and blank fields in the search for first-light objects. While there are a number of well-studied lensing clusters, they are not all ideal candidates for the search of first light objects due to strong ICL contamination or high Zodiacal backgrounds. We will thus, complement the existing HFF and CLASH lensing samples with recently discovered,

high mass, compact clusters such as the CLIO cluster.

The layout of this Chapter is as follows. In Section 2.2 we discuss the group finding algorithm, including how CLIO was identified as a unique viable target for study. Section 2.3 gives an overview of the observations, including data reduction and spectral analysis. In Section 2.4 we derive key physical properties of the CLIO cluster and its member galaxies, and perform preliminary lensing and ICL analysis. Finally, we summarise our main results and draw conclusions in Section 2.5.

2.2 Target Selection

GAMA is a deep spectroscopic survey over ~ 250 square degrees down to $r < 19.8$ mag, providing the largest, highly complete sample of low-mass galaxy groups in the local Universe. CLIO is selected from v8 of the GAMA Galaxy Group Catalogue (G³C; Robotham et al., 2011). Groups in the G³C are identified using a modified friends-of-friends (FoF) algorithm, which is run on the same distribution of galaxies projected onto the sky, as well as along the line of sight. Galaxies identified as linked to each other in both projections are considered to be grouped together; this successfully eliminates any redshift space distortion effects. Parameters for the FoF algorithm are calibrated and optimised by running it on a series of bespoke mock galaxy catalogues whose geometry and luminosity function match those of the GAMA survey (Merson et al., 2013).

We analyse galaxy groups/clusters from the G³C based on a combination of various selection criteria. Selection is initially based on cluster concentration, since it may be easier to remove JWST stray light gradients in compact clusters with lower ICL fractions. Concentration estimates are derived by fitting a Navarro-Frenk-White (NFW; Navarro et al., 1996) profile to the enclosed stellar mass within the 50th, and 68th percentile radii, with concentration as a free parameter. We

model the number of expected lensed sources between $1 \leq z \leq 8$ as a function of group mass and concentrations, calculated assuming a singular isothermal sphere (SIS) density profile, with magnification bias and high redshift galaxy densities based on the luminosity functions of Bouwens et al. (2015). The lensed image rates are shown as overlaid contours in Figure 2.1.

We require a cluster redshift that is optimal for lensing studies of high-redshift galaxies with JWST. We find that the cluster redshift must be kept to $z \lesssim 0.5$ in order to minimize the effects of the cluster spectral energy distribution (SED) in the wavelength range of $\lambda = 3 - 5\mu m$, where the JWST Near-Infrared Camera (NIRCam) is the most sensitive and the Zodiacal background is darkest. The increased ICL surface brightness at these lower redshifts is compensated for by lower, near-IR K-corrections of similar clusters at higher redshifts.

Clusters are further sub-selected from the sample based on the caustic mass estimation technique (Diaferio, 1999; Alpaslan et al., 2012). Cluster members are analysed in a redshift-space diagram in which the projected radial separation from the group centre is plotted against the line-of-sight velocity relative to the group centre of mass. Within this phase-space, the spherical infall model (Regös & Geller, 1989) predicts the existence of trumpet shaped caustics which define the escape velocity of the cluster as a function of radial distance from the cluster centre. Thus, galaxies which fall outside of the caustics are not considered to be gravitationally bound to the cluster. Through this analysis we select clusters with optimal distribution within this phase-space. Finally, we examine the redshift distribution of cluster members to check for potential merging systems or line-of-sight alignments, which complicate lensing studies.

Original identification of the CLIO cluster in version 5 of the G³C is GAMA-100033. However, more recent versions (v6 and onwards) label the cluster as GAMA-100050. To avoid any ID ambiguity, we provide a unique name for the

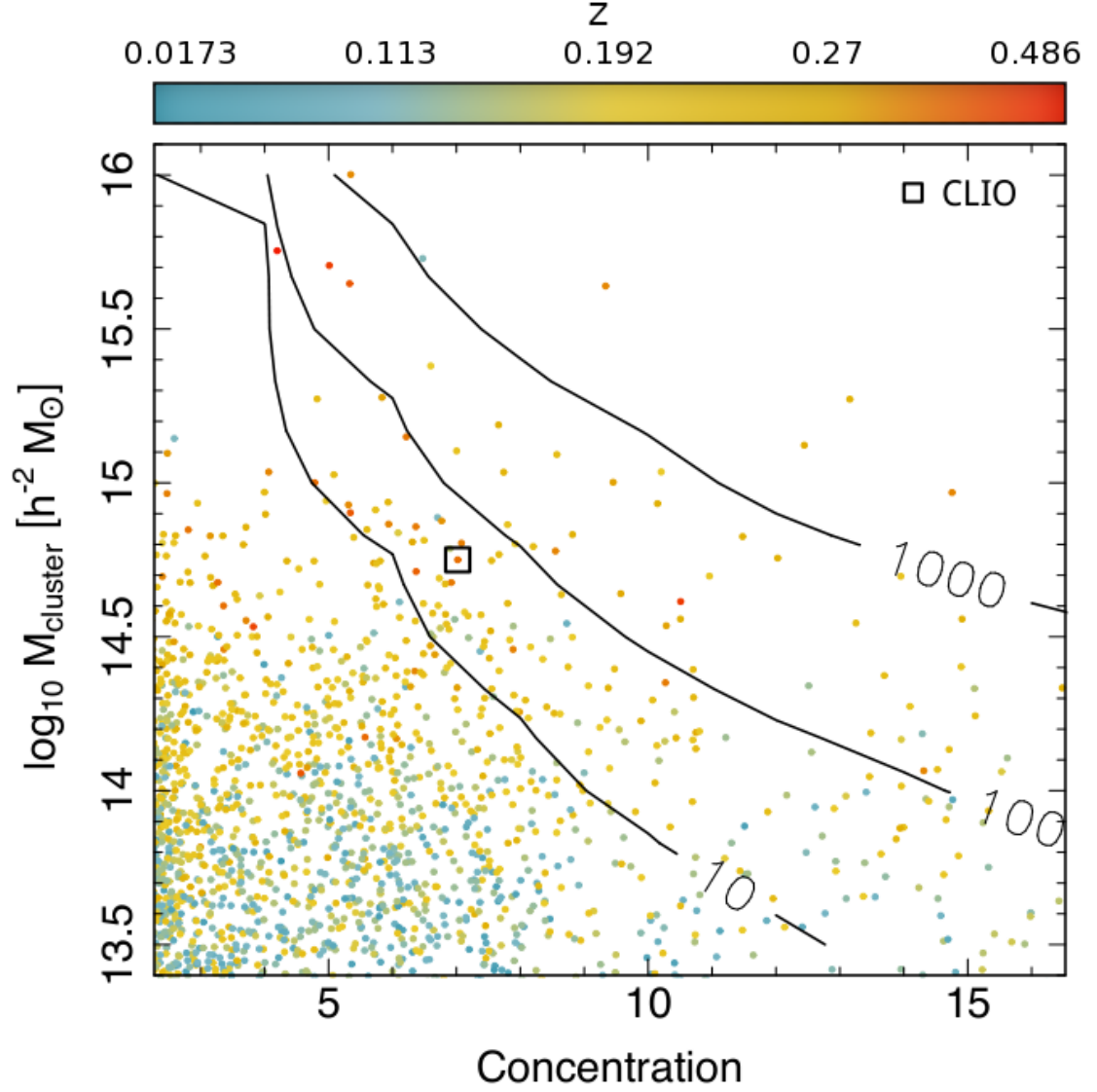


Figure 2.1: Dynamical masses as a function of concentration for GAMA groups, with each point coloured by the group’s median redshift. Contours represent the estimated number of lensed galaxies between $1 \leq z \leq 8$ calculated assuming a singular isothermal sphere (SIS) density profile, with magnification bias and high redshift galaxy densities based on the luminosity functions of Bouwens et al. (2015). CLIO is identified by the black square.

cluster. We take our inspiration from the Multi Unit Spectroscopic Explorer (MUSE) on which a vast majority of this preliminary work is based. We name the cluster after one of the nine muses of Greek mythology, the muse of history, Clio.

We identified this cluster as a promising candidate for follow-up observations; based on its unique combination of implied high mass and concentration, as well as the detected presence of lensing arcs in ground based imaging. CLIO has a median redshift of $z = 0.42$ and is estimated to have a dynamical mass of $\sim 6 \times 10^{14} M_{\odot}$, and a concentration of 6.3. From GAMA there are 14 spectroscopically confirmed members and the central galaxy ID is 323174 (G³Cv9). The cluster has an initial velocity dispersion estimate of 633 km s^{-1} and a radius of $R_{50} = 0.66 \text{ Mpc}$. This cluster's combination of high mass and concentration (which is sufficient to generate well-resolved lenses, as evidenced by HST imaging), as well as a redshift that is favourable to lensing high redshift galaxies, makes CLIO ideal for our targeted study.

2.3 Observations and Data Reduction

Optical imaging and spectroscopy of the galaxy cluster CLIO were obtained as part of program 096.B-0605(A) (PI Conselice) at the European Southern Observatory (ESO) Paranal facility. Ancillary infrared observations were made as part of *Spitzer* Cycle 13 Program 13024 (PI Yan). These observations were made as part of a study into the most dark matter dense galaxy clusters identified within the GAMA survey, in an effort to study the properties of these unique objects.

2.3.1 Optical Imaging

Dual band photometric data were obtained with the FOcal Reducer/low dispersion Spectrograph (FORS2) multi mode instrument mounted on the VLT at ESO's

Paranal Observatory (Appenzeller et al., 1998). CLIO was observed at a pointing of $\alpha = 08:42:21.2$, $\delta = +01:38:26.3$ using the FORS2 High Resolution Collimator equipped with a mosaic of two 2k x 4k CCDs, providing a pixel scale of 0.125 arcsec pixel⁻¹ over a 4.25' x 4.25' field of view (FoV). Observations were carried out on the nights of December 13th 2015 (12x580s) and January 15th 2016 (10x600s) in the R_SPECIAL and g_HIGH filters respectively. An earlier observation run with the g_HIGH filter was initiated on the night of December 22nd 2015, but it was subsequently aborted due to sky saturation by the moon.

The photometric data were reduced using the dedicated FORS2 instrument pipeline (v. 5.3.5), implemented within the ESO data reduction environment Reflex v. 2.8.5 (Freudling et al., 2013). The pipeline performs all standard reduction procedures including bias subtraction, cosmic rays removal, flat-field corrections and astrometry. Final science images are 2 x 2 binned, resulting in a final pixel scale of 0.25 arcsec pixel⁻¹ and a projected field of view of 8.3' x 8.3'. However, due to vignetting the effective field of view is reduced to $\sim 6.8' \times 6.8'$. Reduced science images are then background subtracted and median combined with WCS offsets using standard IRAF tasks, imarith and imcombine.

We performed aperture photometry using SExtractor (Bertin & Arnouts, 1996) in dual-image mode. We apply a 3 x 3 pixel Gaussian filter over both images, and set a detection threshold of 0.5σ for optimal identification of faint background sources. The FORS2 *r*-band image is used as a reference in which centroids and apertures are calculated for photometric measurements of both *r*, and *g*-band images. We use Kron-like elliptical apertures from SExtractor in order to calculate final object magnitudes. Due to technical issues, standards were not taken for the *g*-band observations, so photometric calibrations of both bands are undertaken. We adjusted magnitudes to the Sloan Digital Sky Survey (SDSS) system using a set of standard stars within our observed field. We corrected

instrumental magnitudes for atmospheric extinction¹ and calculated photometric zeropoints. Finally, we calculate colour transformation coefficients in order to standardise our measurements.

We obtain additional data from the first public data release of the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP; Aihara et al., 2018b). Along with g, r, i, z, y imaging we obtain catalogue data, including forced photometry (measurements performed in all epochs based on location from co-added images) and photometric redshift estimates. We utilise the g and r -band HSC photometry to perform additional checks on our photometric calibration and colour transformations.

2.3.2 IR Imaging

We also obtained *Spitzer* InfraRed Camera (IRAC; Fazio et al., 2004) observations in its 3.6 and 4.5 μm channels. These data were taken on 2nd February 2016 as part of Cycle 13 Program ID 13024 (PI Yan). The observations were done in two Astronomical Observation Requests (AORs), one for each channel. The two AORs were executed back-to-back, and hence the images in both channels essentially have the same orientation. The $5.2' \times 5.2'$ IRAC field-of-view is large enough to cover the entire cluster, and hence we only dithered around one pointing. IRAC takes images in both channels simultaneously: if one chooses to centre the target field in one channel, an adjacent flanking field will be automatically obtained at the same time in the other channel, and there is a separation of $1.52'$ in between the edges of the two fields. We used 100-second frame time and medium-scale cycling dither of 120 positions, which resulted in a total integration of 12,000 seconds in both channels. The dithering scale is large enough such that the two field-of-views have

¹obtained from the ESO quality control database http://www.eso.org/observing/dfo/quality/index_fors2.html

no gaps after mosaicking. However, as the flanking fields in the two channels are at the opposite sides of the target field, only the target field itself has data in both channels.

Spitzer Science Center (SSC) reduces all raw data for users through its standard pipeline to the point of producing Basic Calibrated Data (BCD), which are individual exposures removed of various instrumental effects (such as dark current subtraction, flat-fielding, etc.) In recent years, the pipeline has extended its capability to mitigate several artifacts commonly found in IRAC data (such as “column pulldown”, “banding”, etc.), and produces “Corrected BCD” (CBCD) images. Our further reduction of the data involved stacking the individual exposures, which was based on the CBCD images retrieved from the *Spitzer* Heritage Archive (SHA). For this purpose, we utilized the MOPEX software (v. 18.5.0) developed at SSC, which is capable of fine-tuning the astrometry of individual images, doing proper sub-sampling of the image and projection, and summing the images using a variety of algorithms. We removed the background of each CBCD image by subtracting its background map derived from the image using a median filter of 45×45 (native) pixels in size. We adopted a pixel scale of $0.6''$ (i.e., about half of the native pixel scale) for the final mosaics. The projection centre and the image dimensions were chosen such that the final mosaics in both channels would be precisely aligned. The stacking was done by a linear weighted sum of input pixels with weights equal to the area overlap with the output pixel, which is the default stacking scheme of MOPEX. In the process, 3σ outliers were rejected before combining.

2.3.3 MUSE Optical Spectroscopy

On the nights of the 12th (7x900s exposures) and 13th December 2015 (7x900s exposures), spectroscopic data of the CLIO cluster were obtained with the MUSE Integral Field Spectrograph located at the VLT (Bacon et al., 2010). The spectro-

graph offers a wavelength coverage of 480 - 930 nm with a mean spectral resolution of $R \sim 3000$. The ~ 1 arcmin² field of view is provided by MUSE's wide field mode, resulting in a spatial resolution of 0.2 arcsec pixel⁻¹.

The MUSE data were reduced and combined into a single datacube using the instrument pipeline (v. 1.6.2) in the ESO Reflex environment. The pipeline works on individual exposures, performing bias subtraction, flatfielding and wavelength calibration across the full wavelength range. Flux calibration is then performed using reference stars and the 14 individual exposures are combined into a single datacube with a resulting ~ 1.8 arcmin² field of view. The datacube was further processed with the ZAP pipeline which makes use of the Zurich Atmosphere Purge (Soto et al., 2016) code to remove residual sky contamination using principal component analysis.

2.3.4 Spectral Analysis

Initial object detection and spectral analysis was performed using the MUSE Line Emission Tracker² (MUSELET). This tool splits the datacube into line-weighted pseudo-narrow band images of 6.25 Å width across the full wavelength range of the MUSE datacube. The continuum is estimated from spectral medians of ~ 25 Å on either side of the narrow band region. SExtractor is then used to detect line emission in the pseudo narrow-band images, a composite catalogue is created in which continuum sources can be isolated, and redshifts estimated. A total of 44 MUSELET detections are found and used to cross-reference our manual extractions as described below.

Object detection was performed by running SExtractor on the FORS2 *r*-

²MUSELET is an open-source python package developed by the MUSE Consortium as part of the MUSE Python Data Analysis Framework (MPDAF) <http://mpdaf.readthedocs.io/en/latest/index.html>

band image. We use the IRAF task `wregister`, to transform the output segmentation map and the FORS2 *r*-band image to the same pixel scale and FoV as the MUSE datacube. The resulting spatial profiles provided by the segmentation map were then used as a basis to extract 1D weighted spectra and variance from the MUSE datacube using a custom MATLAB code. The chosen SEXTRACTOR parameters caused some deblending of the most extended sources into multiple objects. Where this occurred, the objects were manually inspected and segmentations regions merged before extraction of spectra. Redshifts were then determined using a customised version of the Manual and Automatic Redshifting Software (MARZ), which uses a cross-correlation algorithm to match input spectra against a number of emission and absorption-line template spectra (Hinton et al., 2016). Customisation of the software was performed in order to include a further ten high redshift spectral templates. These additional templates were obtained from zCosmos (Lilly et al., 2009), the VIMOS-VLT Deep Survey (VVDS; Le Fèvre et al., 2013) and UDSz (ESO Large Programme 180.A-0776, PI: Almaini, Bradshaw et al., 2013; McLure et al., 2013, private communication). All reduced spectra are passed through the MARZ software, and along with an initial redshift estimate, each spectrum is assigned a quality operator (*QOP*) based on the cross-correlation strength. Each spectrum is then visually inspected in order to improve redshift determinations where necessary and assign quality flags. Each redshift is assigned a final quality flag (*Q*) with values ranging from 1 to 5 based on the following specifications:

- 1: Unknown redshift with no evident spectral features, determined by cross-correlation only.
- 2: Possible but uncertain redshift, single undetermined spectral feature or low cross-correlation strength.
- 3: Probable redshifts with a single strong spectral feature or numerous faint absorption features.

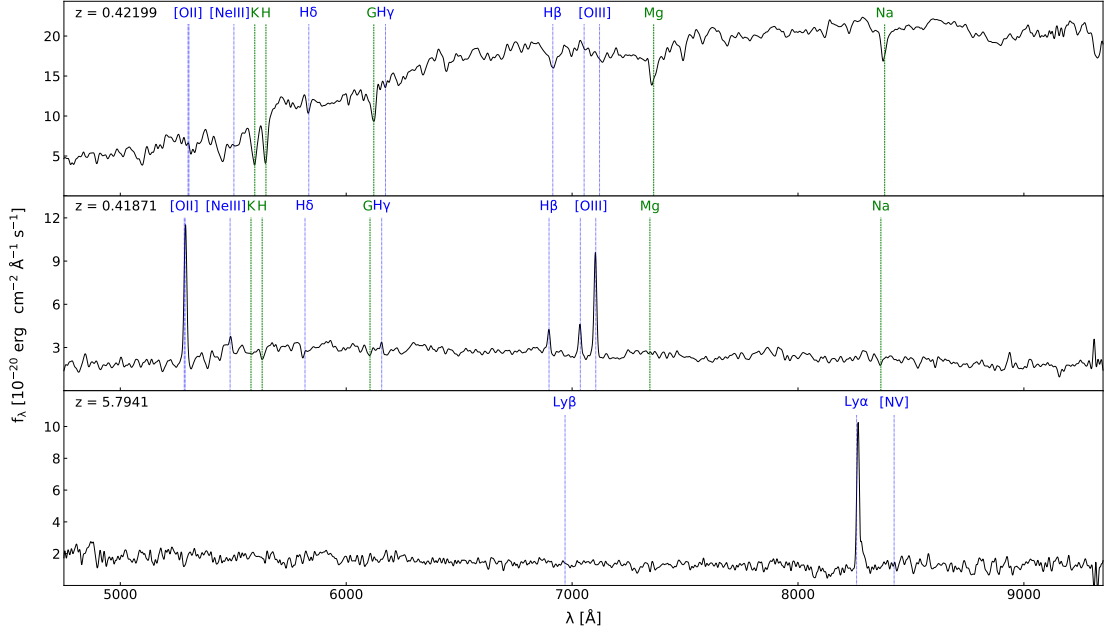


Figure 2.2: Examples of 1D spectra extracted from the MUSE datacube. From top to bottom, we show: a quality level 4 spectrum identified through multiple absorption features (marked by green dashed lines), a quality 4 cluster member spectrum based on multiple emission lines (mainly [O II] and [O III], marked by the blue dotted lines), and a quality 3 high redshift spectrum identified through the strong asymmetrical Ly α feature.

- 4: Secure redshifts with multiple strong spectral features present and a high cross-correlation strength.
- 5: Secure redshift of non-extragalactic source matched to a stellar template.

Emission line redshifts determined by MUSELET provide sufficient reference in order to manually fit a number of uncertain spectra within the MARZ GUI. Of the 44 MUSELET detections, 35 fit well to the initial MARZ estimates, 6 were used to manually adjust redshifts, and 3 were found to be spurious emission line detections. Additionally, 61 single emission line sources were identified by MUSELET which were used to confirm or reject fits to Ly α or [O III] lines. Typical examples of spectra extracted from the MUSE datacube can be seen in Figure 2.2.

A total of 406 objects were detected within our observed MUSE field. Of these, 184 of the extracted spectra were of high enough quality for redshifts to

Table 2.1: Summary of redshift determinations and quality flags assigned to spectra extracted from the MUSE datacube.

Q	Number	Fraction	Redshift Range
1	168	41.4%	-
2	54	14.0%	-
3	97	23.2%	$0.0001 \leq z \leq 6.49$
4	80	19.7%	$0.08 \leq z \leq 1.22$
5	7	1.7%	-

be determined. A summary of our redshift detections can be found in Table 2.1. We construct individual redshift catalogues of cluster members and background objects with $Q = 3$ and $Q = 4$ spectra only (with an exception of lensing arcs discussed in Section 2.4.7). Analysis described within this Chapter makes use of the results contained within this catalogue, a sample of catalogue entries and a description of columns is provided in Table 2.2 & 2.3.

2.4 Results

2.4.1 Cluster Membership

Cluster members situated within the MUSE field were identified through the investigation of their spectroscopic redshift distribution, which can be seen in Figure 2.3. The tight clustering found around the previously quoted cluster redshift allowed constraints on membership to be placed within 0.01 of the mean redshift of $z = 0.42$, in which a total of 89 galaxies are situated. The cluster sample predominantly consists of early-type absorption galaxies with easily identifiable H and K spectral features, while 20 members show dominant [O II] and [O III] emission lines. The spatial distribution of spectroscopically identified cluster members can be seen in Figures 2.4 & 2.5.

Further efforts were made in order to identify additional cluster members

Table 2.2: Cluster member spectroscopic redshift catalogue ordered by ID. This table has been truncated and is available in its entirety in the online version of the paper Griffiths et al. (2018). ID's quoted are from this study and correspond to spectra extracted from the MUSE datacube. Columns 4 to 11 provide $g,r,3.6\mu m$ and $4.5\mu m$ magnitudes derived in this study along with their corresponding errors. g,r,i,z and y magnitudes and their corresponding errors taken from the HSC catalogue (Aihara et al., 2018a) are included in columns 12 to 21. We provide k -corrections (calculated following methods outlined in Chilingarian et al. (2010)) for g and r -band photometry in columns 22 and 23. Columns 24 and 25 provide stellar mass estimates detailed in Section 2.4.2, while columns 26 and 27 give DEmP photometric redshifts and their confidence values obtained from the HSC first data release (Tanaka et al., 2018). Finally, we provide spectroscopic redshifts and their quality flags as detailed in this section.

ID	R.A	DEC.	mag_g	mass_g	...	photo_z	spec_z	Q
	[deg]	[deg]	[mag]	[$M_{\odot}$]				
23	130.596	1.654	22.99 ± 0.16	1.57×10^{10}	...	0.40	0.42	4
28	130.591	1.654	23.16 ± 0.12	1.32×10^{10}	...	0.45	0.43	4
34	130.589	1.653	22.67 ± 0.07	2.61×10^{10}	...	0.40	0.43	4
36	130.588	1.653	24.31 ± 0.27	4.69×10^9	...	0.42	0.42	3
41	130.584	1.653	24.21 ± 0.30	5.95×10^9	...	0.47	0.42	4
42	130.595	1.653	21.87 ± 0.05	6.95×10^{10}	...	0.42	0.42	4
43	130.580	1.653	22.98 ± 0.12	1.39×10^{10}	...	0.37	0.42	4
45	130.578	1.652	22.77 ± 0.08	1.83×10^{10}	...	0.43	0.42	4

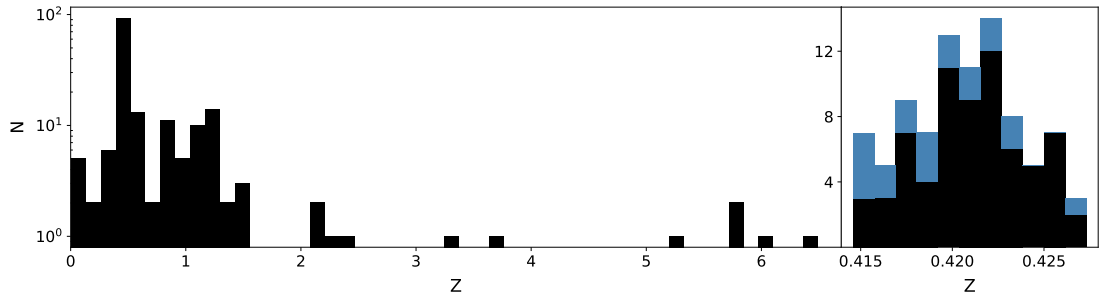


Figure 2.3: Left: Shows the distribution of spectroscopic redshifts within the observed MUSE field. Right: Shows only the objects within the redshifts of $0.41 \leq z \leq 0.43$ in which constraints have been placed on cluster membership. On the right, black represents absorption line galaxies and in blue are objects with emission line spectra.

Table 2.3: Background object spectroscopic redshift catalogue order by ID. This table has been truncated and is available in its entirety in the online version of the paper Griffiths et al. (2018). Columns in this catalogue are identical to that of the cluster member catalogue with the exception of k-correction and mass estimations which are not included due to the redshift limitations of the methods used.

ID	R.A	DEC.	mag_g	...	photo_z	spec_z	Q
	[deg]	[deg]	[mag]				
5	130.591	1.627	25.52 ± 0.62	...	0.36	6.09	3
8	130.580	1.656	24.70 ± 0.30	...	1.21	1.26	3
17	130.588	1.655	22.98 ± 0.09	...	0.58	0.55	4
22	130.588	1.654	25.77 ± 0.77	...	0.77	0.72	3
25	130.586	1.654	26.51 ± 1.24	...	0.97	0.97	3
27	130.584	1.654	24.06 ± 0.20	...	2.08	3.76	3
29	130.580	1.654	23.97 ± 0.20	...	0.51	0.49	4
31	130.572	1.654	23.11 ± 0.12	...	1.24	1.26	3

outside of the MUSE FoV using photometry derived from the FORS2 and IRAC data. Initially, a colour cut was performed, disregarding potential cluster members with $(g - r) > 2$. A linear fit was then applied to the spectroscopically identified red sequence in both $(g-r)$ and $(3.6\mu m-4.5\mu m)$, down to magnitude completeness limits of 25.5 and 19.8 mag, for r and $3.6\mu m$ respectively. Any SExtractor detected objects with colours within 1σ of the fits were assigned as candidates for cluster membership.

We investigate the blue cloud in a similar manner via spectroscopically identified emission line galaxies located within the cluster. As can be seen from the spatial distribution of cluster members in Figures 2.4 & 2.5, there is a strong correlation between the cluster environment and galaxy spectral type. Galaxies identified via emission lines are situated at a mean radial distance of $\bar{r} = 0.23$ Mpc from the cluster centre, whereas absorption type members are found closer to the cluster core at $\bar{r} = 0.16$ Mpc. This truncation suggests that a higher fraction of cluster members beyond the MUSE FoV, are likely to be blue emission line galaxies. The combined

analysis of both red and blue galaxies provides an additional 251 candidate cluster members.

In an attempt to further refine the colour-colour selection of potential cluster members, we utilise photometric redshift data recently made available in the first HSC public data release (Aihara et al., 2018a). Photometric redshifts within the HSC public data release are computed using several independent codes. Each of the codes are trained and verified by performing cross-validation techniques on a test sample, constructed from various spectroscopic and photometric sources (Tanaka et al., 2018).

To identify which of the seven HSC photometric redshifts is best fit to our data, we perform a direct comparison to our spectroscopically identified cluster members. In order to achieve the most accurate results, we only include objects with a confidence level of > 0.5 in our analysis. We define outliers by the conventional definition of $|\Delta z| > 0.1$ and consider both the bias and the scatter of the residual $|\Delta z| / (1 + z)$. Through this analysis, we find that the Direct Empirical Photometric code (DEmP; Hsieh & Yee, 2014) provides the best statistical fit to our spectroscopic redshifts; a comparison can be seen in Figure 2.6. We find an outlier rate of $< 2\%$, a bias of 0.015, scatter of 0.019. Over 80% of the sample have a confidence value above the cut.

We find similar results with the Ephor³, and MLZ⁴ photometric redshifts but with much lower sample numbers after the confidence cut ($\sim 70\%$ and $\sim 30\%$ respectively). We select all colour-colour identified galaxies with a DEmP photometric redshift of 0.42 ± 0.1 for a refined sample of 198 candidate cluster members.

³Extended Photometric redshift (EPHOR) is a neural network photometric redshift code, see Tanaka et al. (2018) for details.

⁴Self-Organizing Map from the machine-learning photometric redshift package by Carrasco Kind & Brunner (2014).

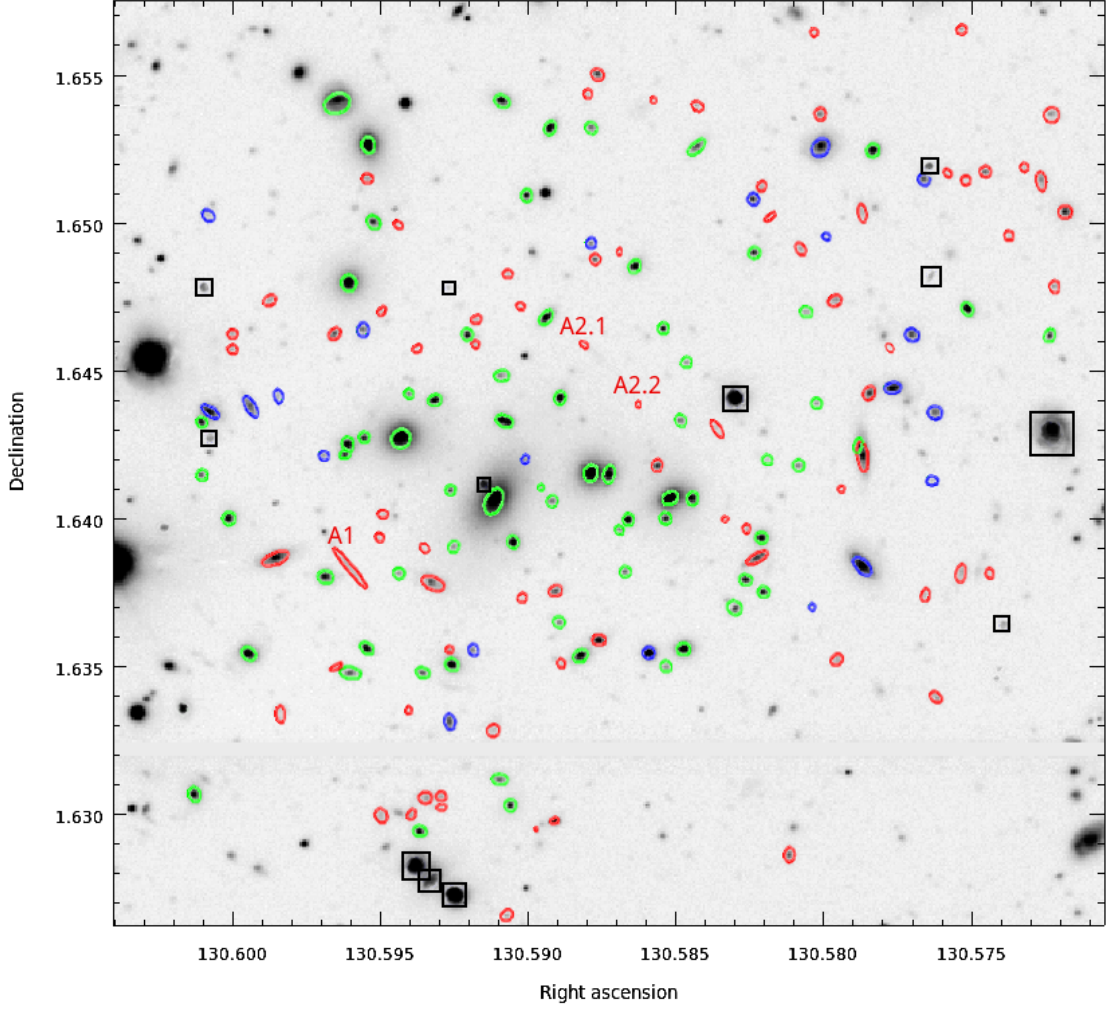


Figure 2.4: Spatial distribution of spectroscopically identified galaxies overlaid on the FORS2 r -band image. Black squares indicate foreground galaxies at $z < 0.41$, green and blue ellipses are absorption and emission line detected cluster members respectively, with redshifts $0.41 \leq z \leq 0.43$. Red ellipses show background galaxies with $z > 0.43$. All ellipses are scaled and positioned by SEXTRACTOR parameters. A1 and A2 show the locations of the lensing arcs as discussed in Section 2.4.7

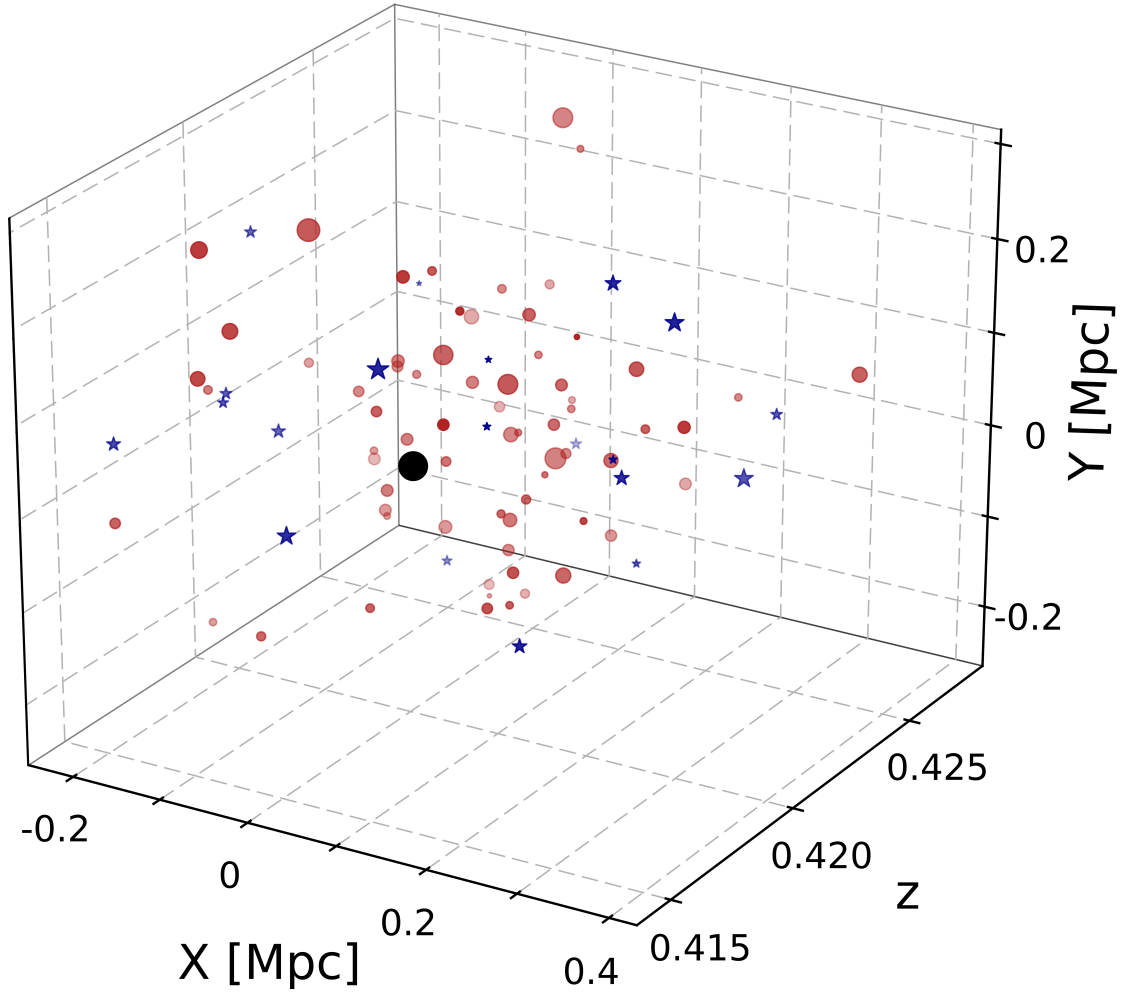


Figure 2.5: 3D distribution of cluster members. The black circle represents the brightest cluster galaxy (BCG), red circles are galaxies fit with absorption dominated spectral templates, while blue stars are cluster members fit with emission line templates. Point sizes are scaled by object area using the SEXTRACTOR parameter ISOAREA_IMAGE.

Throughout this study, we use colour-colour selected members in our analysis only when detailed velocity information is not required. This includes projected cluster radii estimations, cluster centre and concentration analysis, as well as deriving the total stellar mass and luminosity function of the cluster.

2.4.2 Galaxy Populations

For all spectroscopically identified cluster members we measure $(g-r)$ rest frame colours in which K-corrections were performed following methods outlined by Chilingarian et al. (2010).

A clear red sequence can be seen for the spectroscopically identified cluster members within both the FORS2 and IRAC data as shown in Figure 2.7. The cluster members have mean colours of $(g-r) = 1.75$ and $(3.6\mu m-4.5\mu m) = 0.13$ mag. The blue cloud, shown here through the distribution of emission-line galaxies, is observed in the FORS2 data to have a mean colour of $(g-r) = 1.31$ mag. The blue population is not prominent in the IRAC data due to the limited number of objects with corresponding $(3.6\mu m-4.5\mu m)$ colours.

It has been shown that there are tight correlations between optical and near-infrared galaxy colours with stellar mass-to-light ratios that can be modelled via a simple linear equation (Sargent & Tinsley, 1974; Larson & Tinsley, 1978; Jablonka & Arimoto, 1992). For a composite stellar population, the mass-to-light ratio depends on the initial mass function (IMF), the star formation history (SFH) and metallicity distribution. The work of Bell & de Jong (2001) show that through the use of stellar population synthesis (SPS) models, a reliable stellar mass can be estimated that is robust against metallicity and extinction effects. The most robust relations found are in the optical bands, where the age-metallicity degeneracy is beneficial, as it acts to tighten the relation. The work of Bell & de Jong (2001) also shows that dust extinction and reddening effects cancel each other out to

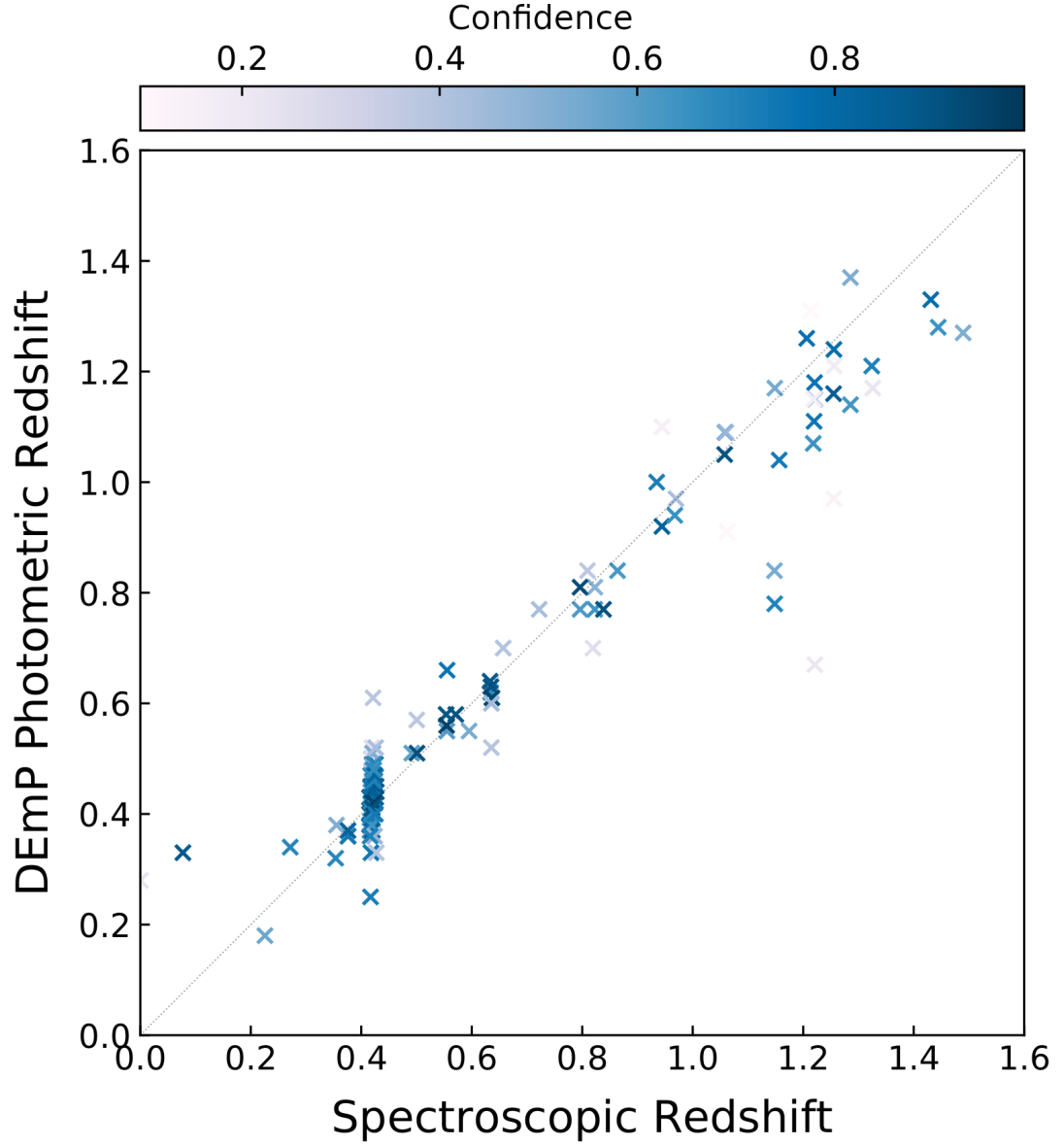


Figure 2.6: Comparison of spectroscopic redshifts found in this study to DEmP photometric redshifts from the first HSC public data release within the range of $0 < z < 1.6$. Points are coloured by the photometric confidence value in which we require a value of > 0.5 for use in our analysis.

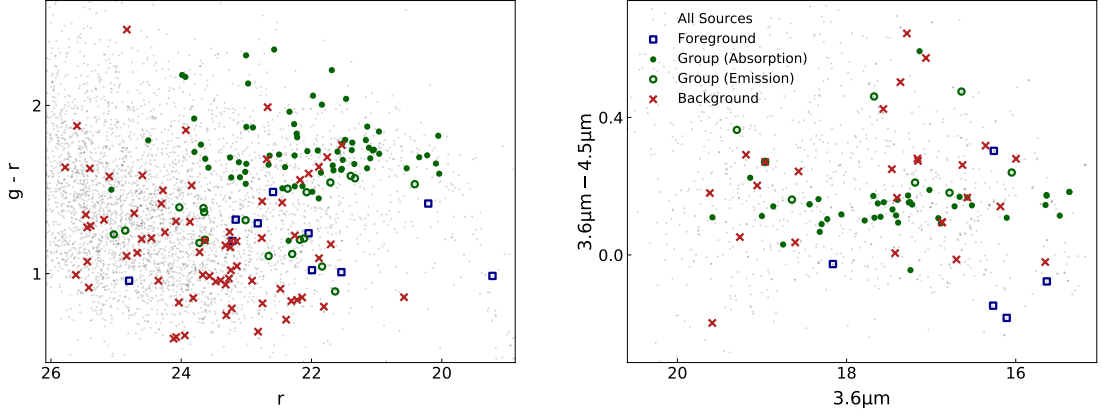


Figure 2.7: Colour-Magnitude relations of CLIO members, foreground and background galaxies. Left panel: Shows $(g-r)$ colour vs r -band magnitude from FORS2 imaging, while right panel shows $(3.6\mu m - 4.5\mu m)$ vs $3.6\mu m$ from IRAC. Green filled circles represent cluster galaxies which exhibit absorption spectra while green empty circles are emission line dominated cluster members. Blue squares are foreground galaxies ($z < 0.41$). Light grey shows all, non-spectroscopically identified objects.

first-order approximation. In this study, we follow the methods outlined in Into & Portinari (2013) which takes into account the asymptotic giant branch phase in order to update colour-mass-to-light relations. We make use of models with exponentially declining/increasing star formation rates (SFRs) Into & Portinari (2013) which more accurately mimics the photometric properties of the Hubble sequence and calculate stellar masses by:

$$\log_{10} \left(\frac{M_*}{L_r} \right) = 1.373 (g - r) - 0.596. \quad (2.1)$$

The total stellar mass estimate of all combined cluster members is $\log_{10} (M_*/M_\odot) = 13.63 \pm 0.1$.

2.4.3 Cluster Properties

Velocity Dispersion

We measure the cluster velocity dispersion σ , with the robust gapper estimator method (Beers et al., 1990). The method uses weighted gaps in velocity space and is calculated as follows; firstly, recession velocities of all cluster members are ordered, gaps and weights between neighbouring pairs are then calculated via $g_i = v_{i+1} - v_i$ and $w_i = i(N - i)$ respectively, where $i = 1, 2, \dots, N - 1$. The velocity dispersion can then be estimated by:

$$\sigma = \frac{\sqrt{\pi}}{N(N - 1)} \sum_{i=1}^{N-1} w_i g_i. \quad (2.2)$$

To account for uncertainties in recession velocities, measurement errors are removed in quadrature as prescribed in Robotham et al. (2011). Using the 89 spectroscopically confirmed cluster members, this method yields a velocity dispersion for CLIO of $(619 \pm 11) \text{ km s}^{-1}$. The total error is calculated via bootstrapping techniques. This value is as expected for a compact, high mass galaxy cluster (Cox, 2000) and comparable to the previous estimate of 633 km s^{-1} from the G³C catalogue.

Cluster Centre

The projected cluster centre is calculated through an iterative process. An initial centre of light is defined from the r -band luminosities of the spectroscopically identified cluster members. The most distant galaxy in projected space is rejected, and the new centre of light is calculated. This process is iterated until only two galaxies remain, the brighter of which is taken as the cluster centre. The projected cluster centre was found to be located at the BCG, in agreement with the G³Cv9 catalogue value at $\alpha = 08:42:21.88$, $\delta = +01:38:26.11$ (Galaxy ID: 323174). This iterative process was repeated to include the colour-colour selected galaxies to

investigate if any bias is imposed by the positioning of the MUSE FOV, but the resulting centre remained unchanged.

Cluster Concentration

Initial estimates of the cluster concentration of $c = 6.32$ are based on fitting the enclosed stellar mass of cluster member galaxies to a NFW profile. Due to the availability of data in the G³C, the concentration is estimated from the ratio of the 50th and 68th percentile radii. The percentile radii are calculated using the default quantile definition, in which cluster members are sorted by ascending radial values from the projected cluster centre and a linear interpolation is performed between the bounding percentiles (Robotham et al., 2011).

Due to the limited extent of our spectroscopic coverage with MUSE, we identify cluster members out to only 0.4 Mpc from the cluster centre. This induces a strong radial bias, providing unreliable radius estimates. Even when including our colour-colour selected sample we find that our calculated radii are biased towards a lower value of $r_{50} = 0.27$ Mpc (in comparison to the G³C value of 0.66 Mpc).

To remain as consistent with previous measurements as possible, here we instead measure the concentration parameter by fitting a NFW profile to the projected number density of cluster members. As a function of radius, a NFW density profile is given by:

$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s} \left(1 - \frac{r}{rs}\right)\right)^2}, \quad (2.3)$$

where r_s is the scale radius, and $\rho_s = \delta_s \rho_c$ is a characteristic density, governed by the dimensionless concentration parameter c_{200} . The characteristic contrast density, δ_s , is given by:

$$\delta_s = \frac{200}{3} \frac{c_{200}^3}{\ln(1 + c_{200}) - (c_{200}/(1 + c_{200}))}, \quad (2.4)$$

and ρ_c is the critical density of the universe at the cluster redshift. The scale radius r_s describes where the density profile transitions from $\rho \propto r^{-1}$ to $\rho \propto r^{-3}$ and is of the form:

$$r_s = \frac{r_{200}}{c_{200}}, \quad (2.5)$$

where r_{200} is the radius at which the density of the cluster is equal to $200\rho_c$. Due to the limited spatial coverage of the MUSE data, we refer to the methods presented in Carlberg et al. (1996) to measure r_{200} via the cluster velocity dispersion by:

$$r_{200} = \frac{\sqrt{3}\sigma}{10H(z)}. \quad (2.6)$$

For $\sigma = 619 \pm 11 \text{ km s}^{-1}$ and cluster redshift of 0.42, we calculate $r_{200} = 1.68 \pm 0.03 \text{ Mpc}$.

With the scale radius as a free parameter, a χ^2 minimization is performed, fitting a NFW profile to the clusters projected number density. We include both spectroscopically and colour-colour selected members to find a scale radius of $r_s = 0.22 \pm 0.01 \text{ Mpc}$. Equation 2.5 then yields, $c_{200} = 7.61 \pm 0.43$, a higher value than the initial estimate of 6.32. As the fitting procedures used in this work are not exactly the same as those from the previous concentration estimate, some discrepancy is expected between results. We believe that with the larger dataset available in this work, the concentration value obtained here is significantly more robust than the previous estimate.

We compare our results with lensing clusters selected from the CLASH survey. Merten et al. (2015) employs comprehensive lensing analysis to derive a concentration-mass (c-M) relation of 19 X-ray selected CLASH clusters between redshifts 0.19 and 0.89. The work reconstructs surface mass density profiles in order to derive NFW parameters. Merten et al. (2015) finds a concentration distributed around $c_{200} \sim 3.7$ and an upper value of 4.7 for the MACS J1423+24 cluster. Siegel

et al. (2018) combine gravitational lensing with multiwavelength analysis on 6 CLASH clusters and find good agreement with that of Merten et al. (2015).

The NFW prescription predicts that at a given redshift, halo concentration is expected to decrease systematically with increasing mass (Navarro et al., 1996). As CLIO was selected because of its unique combination of high mass and concentration, extrapolations of c-M relations are likely to provide an underestimate of the total cluster mass. Adopting the method presented in Merten et al. (2015), we find $M_{200} \approx 1.2 \times 10^{14} M_{\odot}$. This is a factor of 5 difference from the G³C initial estimate of $6 \times 10^{14} M_{\odot}$, and thus likely cannot be used as a reliable mass estimate for this cluster.

Our measured concentration value of $c_{200} = 7.61 \pm 0.43$ confirms our initial assumption of the high concentration of the CLIO cluster. Such a high concentration is also useful for producing strong lensing features. This can explain the presence of the giant arcs in this cluster, and may be indicative of a triaxial halo with its main axis along the line of sight.

2.4.4 Luminosity Function

Through the analysis of the absolute r magnitude luminosity function, we can obtain insight into the galaxy population of the cluster, unbiased by selection effects of limited spectroscopic coverage. For a previously unstudied cluster such as CLIO, the luminosity function can also provide information on the dynamical, and evolutionary state of the cluster, as well as serve as a comparison to other similar clusters.

The cluster luminosity function (LF) is defined as the statistical excess of galaxies along the line of sight of the cluster, with respect to a field sample. This implies that the background contribution along the cluster line of sight is equal to that of field samples. However, it is often the case that galaxy contaminants

within the cluster or control field counts adversely affect the determination of the cluster LF.

We determine galaxy counts for both the cluster red sequence and blue cloud using our calibrated FORS2 g and r -band magnitudes. We select galaxies within a 3σ fit of the spectroscopically identified red sequence ($g-r$) colour, down to the r -band photometric completeness limit of -16.5 Mag. We further select all galaxies with colour values below the fit as blue cloud members. Initially, we apply corrections to both data sets based on our MUSE spectroscopy in order to remove foreground source contamination in the cluster line of sight. The data are then binned in steps of 0.5 mag and a total cluster value is calculated through the addition of number counts within respective bins. Finally, we normalise number counts to units of $\text{Mpc}^{-2} \text{ mag}^{-1}$.

Without averaging over many clusters, statistical background subtraction can lead to large errors in the LF due to cosmic variance (e.g., de Propris et al., 1999). An alternative approach is to use spectroscopic data to efficiently estimate background counts without the need for statistical methods (Muzzin et al., 2007). However, due to limited spectral coverage we are unable to obtain robust background estimates in this study. Instead, we make use of HSC data to select a field sample from regions in close proximity to the cluster. This method has been shown to be comparable to that of the statistical methods (see Driver et al., 1998). In order to avoid contamination from cluster member galaxies, we select by eye 4 arbitrary field regions well outside the clusters virial radius. We define a minimum radial distance for field sample selection as twice that of r_{200} from the cluster centre, corresponding to ~ 3 Mpc. We follow the methods outlined above to derive a total, normalised galaxy count in each of the 4 fields. To further negate any statistical fluctuations within the individual fields, we compute a final, composite field sample by taking the average galaxy counts in each bin from the 4 normalised fields.

We correct for background contamination by subtracting the control field number counts from the total cluster count in corresponding bins. The resulting LF is well described by a Schechter function with a slope of $\alpha = -1.35 \pm 0.05$ and a characteristic magnitude of $M_r^* = -21.54 \pm 0.04$ Mag. We calculate confidence intervals on the Schechter parameters via 1000 bootstrapping iterations in which we randomly re-sample 5% of the data. The best fit Schechter function to the total LF is represented by the solid black line in Figure 2.8, along with renormalised fits to the red and blue galaxy distributions.

When considering variations in magnitude range and cluster redshift, we compare M_r^* and α values with composite cluster luminosity functions found in studies such as de Propris et al. (2003) and Christlein & Zabludoff (2003) ($M_r^* = -20.07, -21.14$ and $\alpha = -1.28, -1.21$ respectively). These works (amongst others), find little variation in cluster luminosity functions with various cluster properties. Thus, it is not unexpected that we find consistent results here. At the faint end, we find the number density of blue galaxies increases beyond that of the red population. This can be expected for a cluster at this redshift due to the Butcher-Oemler Effect (Butcher & Oemler, 1984; Andreon et al., 2004) in which it has been observed that the fraction of blue galaxies in clusters rises with increasing redshift. Further, this supports our initial assumptions that our spectroscopic blue galaxy population is significantly truncated by the limited FoV of our MUSE observations.

2.4.5 Intracluster light

Intracluster light is the luminous stellar component, gravitationally bound to the cluster potential, but not to a particular galaxy. The ICL is thought to be formed via tidal stripping of stars during the hierarchical accretion histories of galaxy clusters and groups (Lin & Mohr, 2004; Contini et al., 2014). Thus, investigations

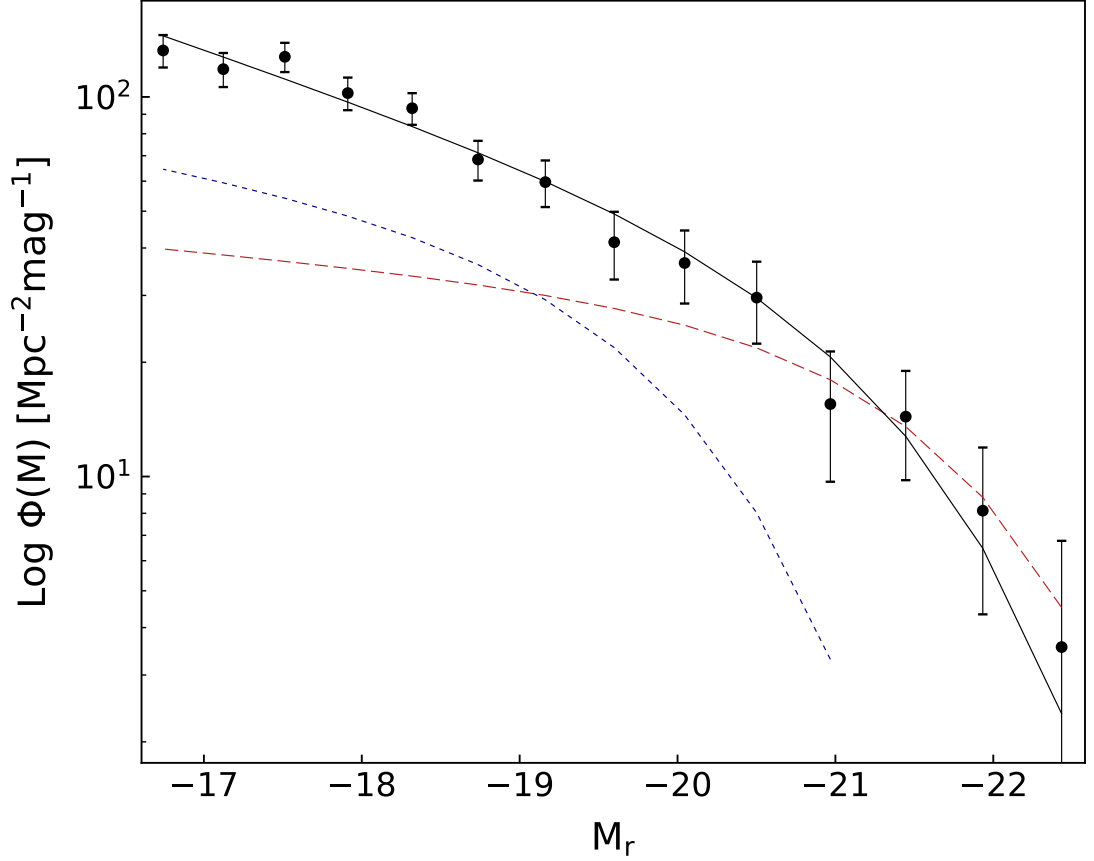


Figure 2.8: The total r -band, cluster galaxy count for CLIO, represented by black circles with uncertainties calculated considering both photometric and Poissonian errors. Data are split into 0.5 mag bins and are background corrected and normalised. Black solid line represents the best-fit Schechter function to the total cluster galaxy count. Red dashed, and blue dotted lines represent the best-fit Schechter function to the renormalised red sequence and blue cloud respectively. As the red and blue curves in this plot have been renormalised to match the total, the scales are not comparable and are shown for reference only.

of the ICL have provided detailed insight into the formation history of galaxy clusters.

Working with a background subtracted r -band image, we measure the ICL as a fraction of the total cluster luminosity within the cluster core. We first mask everything outside a 200 kpc radius from the BCG. We further mask stars and the intervening area between CCD's due to increased noise levels. This can be seen as the left image in Figure 2.9. Object detection is then performed by running *SEXTRACTOR*, where we obtain x and y positions of objects as well as initial estimates of the effective radii R_e , position angles and axis ratios. Cluster members are then isolated from background and foreground galaxies using our detailed MUSE spectroscopy. Values obtained via *SEXTRACTOR* are then used as initial parameters to model all non-cluster objects using *GALFIT* (Peng et al., 2010).

To best estimate the local sky background, we create postage stamps centred on each object. When the galaxy can not be isolated successfully, we fit multiple objects simultaneously. A single Sérsic profile is fit to each galaxy, and the background is simultaneously modelled as a constant. A PSF estimated from a number of bright, non-saturated stars found within the cluster core is convolved with the profiles within *GALFIT*. Each fit is manually checked through inspection of both the model and residual image, adjustments are made where necessary and in a number of cases an additional Sérsic profile was included. An illustration of the model fitting process is shown in Figure 2.10. Each model was then extracted in order to form a composite model of all background and foreground objects. This composite model is then applied to the masked r -band image resulting in a cluster member-only residual which can be seen in Figure 2.9, middle.

We repeat this process, this time modelling the cluster members, a number of the larger galaxies are modelled with multiple Sérsic profiles in order to achieve the best fits. We further remove cluster members from the full image and thus

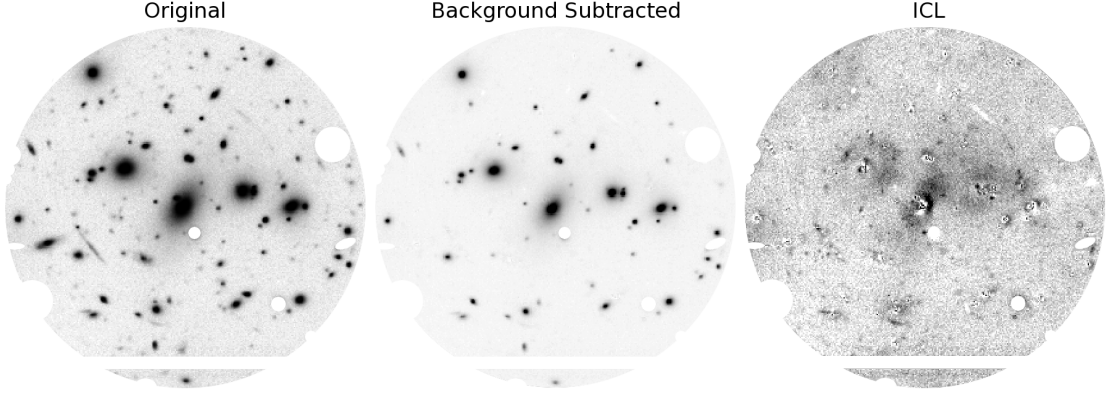


Figure 2.9: Visual representation of the full GALFIT modelling procedure. Left: Shows the original FORS2 r -band image with initial masking applied. Centre: Shows a cluster only residual after subtraction of the composite foreground and background galaxy GALFIT model. Right: Shows the residual ICL model after subtraction of the composite cluster model but before masking of the cluster member galaxy central regions.

leave only the residual ICL component as seen on the right of Figure 2.9. Finally, we apply additional masking to the central regions of some of the cluster members in order to avoid any residual contamination from the GALFIT modelling.

By comparing the total flux in the cluster member image to that of the ICL image, we can get a rough estimate of the ICL fraction of CLIO. This method provides an ICL stellar mass fraction of $7.21 \pm 1.53\%$, where error is estimated from the variance on the ICL flux (f_{ICL})

$$\delta F_{\text{ICL}} = \sqrt{\left(\frac{\sigma_{\text{ICL}}}{f_{\text{total}}}\right)^2 + \left(\frac{f_{\text{ICL}}\sigma_{\text{total}}}{f_{\text{total}}^2}\right)^2}, \quad (2.7)$$

where σ is the standard deviation of the flux. In Figure 2.11, we compare the ICL fraction of CLIO with the cluster ICL studies of Krick et al. (2006), Presotto et al. (2014), Burke et al. (2015), Morishita et al. (2017) and Jiménez-Teja & Dupke (2016). It should be noted that there is currently no standard method for the determination of ICL fractions, as such each study mentioned here employs various limiting radii and masking processes. The methods presented here are motivated by the works of Presotto et al. (2014) and Morishita et al. (2017). These studies

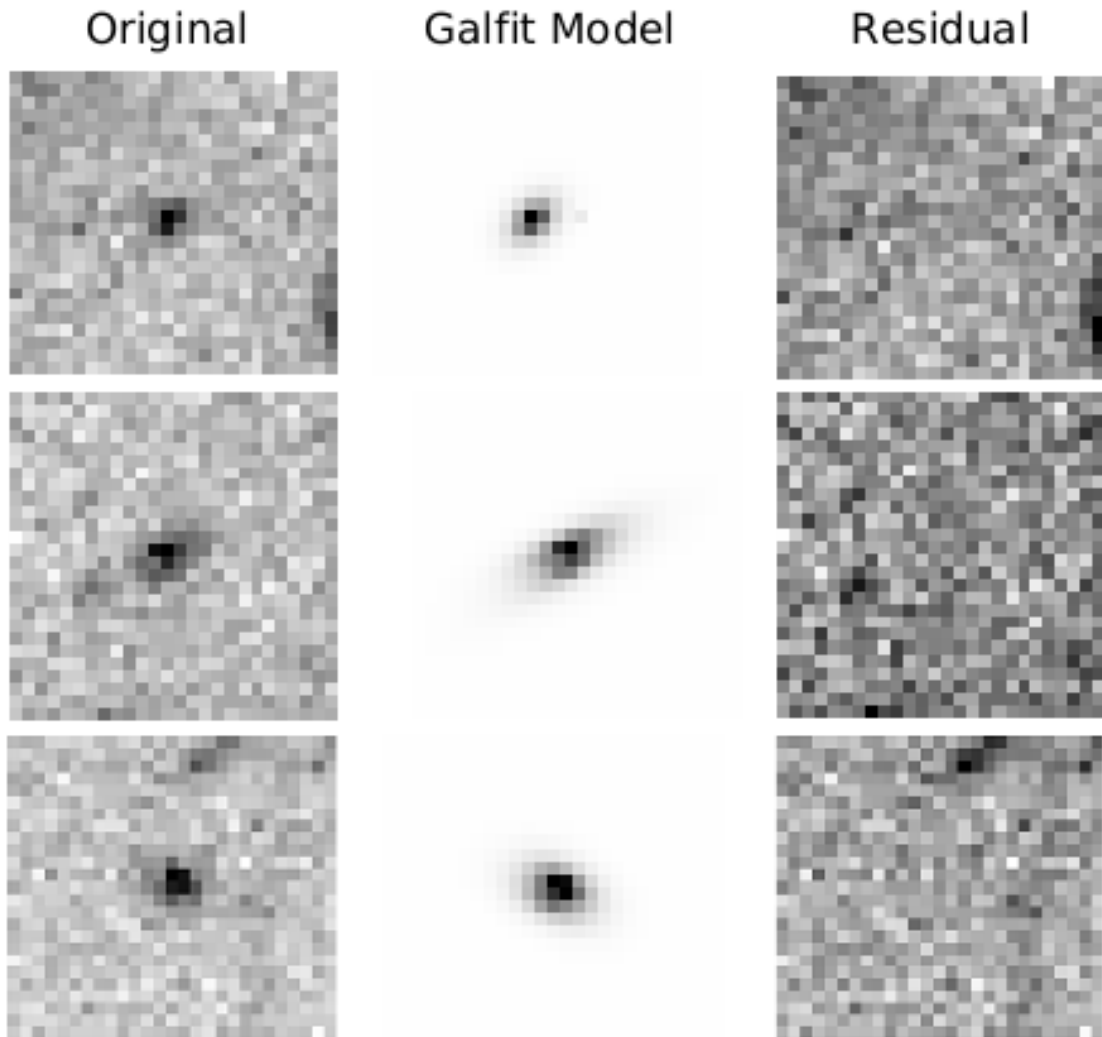


Figure 2.10: Illustration of GALFIT modelling procedure. Left column shows postage stamp taken from FORS2 r -band image. Central column shows the GALFIT Sérsic fit while the right column shows the residual after model subtraction.

use GALFIT based residual modelling to eliminate contaminating galaxy light in order to determine ICL fractions. Whereas, Krick et al. (2006) adopts various modelling procedures to remove galactic light via masking. Jiménez-Teja & Dupke (2016) use methods based on Chebyshev Rational Functions (CHEF; Jiménez-Teja & Benítez, 2012) while Burke et al. (2015) applies a surface brightness threshold. We primarily compare our results with those of Morishita et al. (2017), whose study of six clusters between $0.30 < z < 0.55$ find ICL fractions between 7 and 23%. Our results here show that CLIO is consistent with the lower end of this distribution, matched only by the MACS1149 cluster at a higher redshift of $z = 0.54$. Presotto et al. (2014) finds the MACSJ1206.2-0847 cluster has a low ICL fraction of 5.9%, comparable with that of CLIO. Burke et al. (2015) find values in the range of 2 - 3% at a redshifts of $z \sim 0.4$, however due to the variation in methods, a direct comparison with those found in this study is tenuous. We show here that the low ICL fraction for the CLIO cluster is comparable with various clusters situated at similar redshifts. Thus, when considering the CLIO cluster for JWST lensing studies, this low ICL fraction is ideal in order to maximise the detection of faint lensed sources.

We measure the surface brightness profile of the ICL and total cluster light by splitting the image into radial annuli. We construct 25 radial annuli such that they contain equal areas of $\sim 150 \text{ arcsec}^2$. The recovered profiles can be seen in Figure 2.12. We find that there is a high degree of variation in the cluster radial profile due to radial positions of cluster members. In the outer regions, this is also enhanced by initial masking of stars and the CCD gap. Similarly, noise is induced in the ICL profile by initial masking effects, and also residuals from the galaxy modelling procedure.

To account for these fluctuations, we bin the data and fit a de Vaucouleurs profile to both the ICL, and cluster surface brightness profiles. The resulting ICL

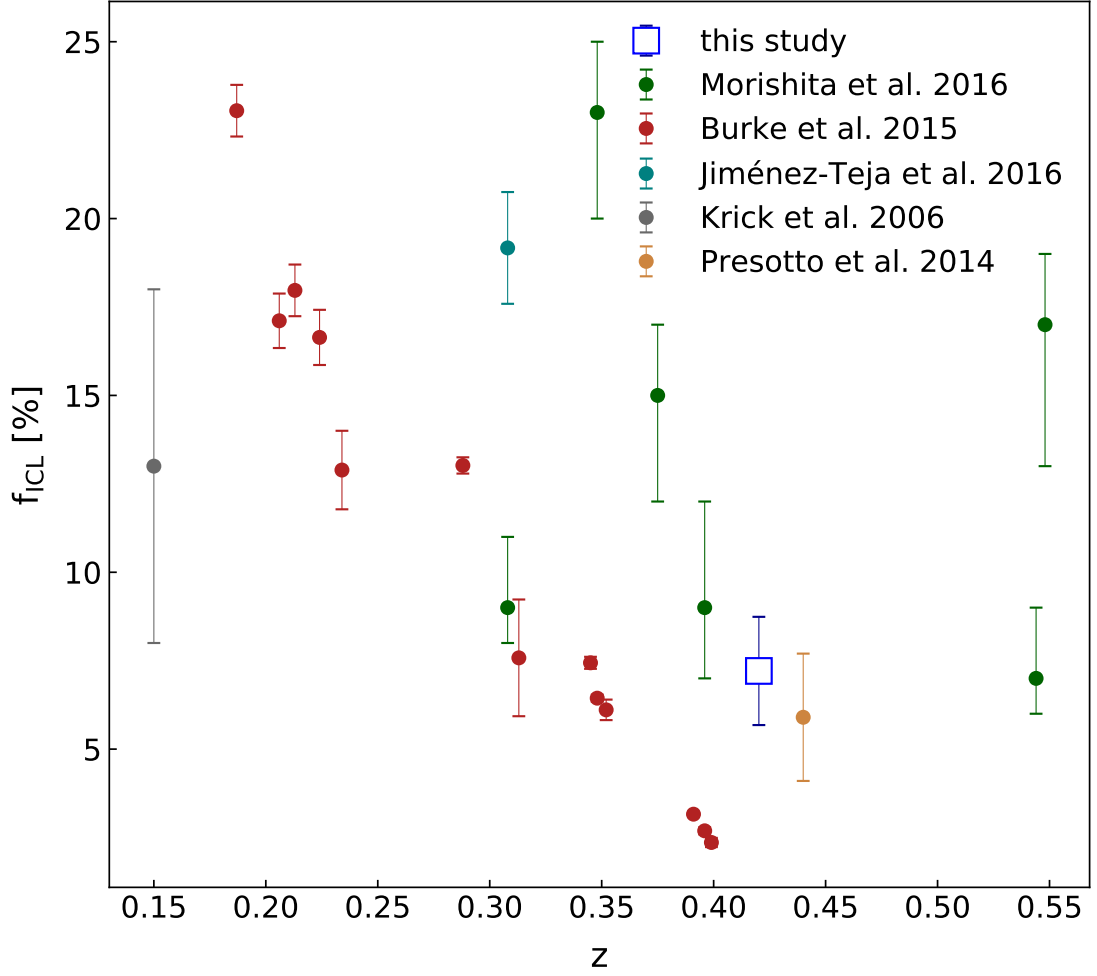


Figure 2.11: Comparison of galaxy cluster ICL fractions with cluster redshift. The ICL fraction obtained in this work is marked by an open blue square while other studies are marked with coloured points. As the works of Presotto et al. (2014) (yellow) and Morishita et al. (2017) (green) both use GALFIT residual modelling, their results are likely the most consistent with those found within this work.

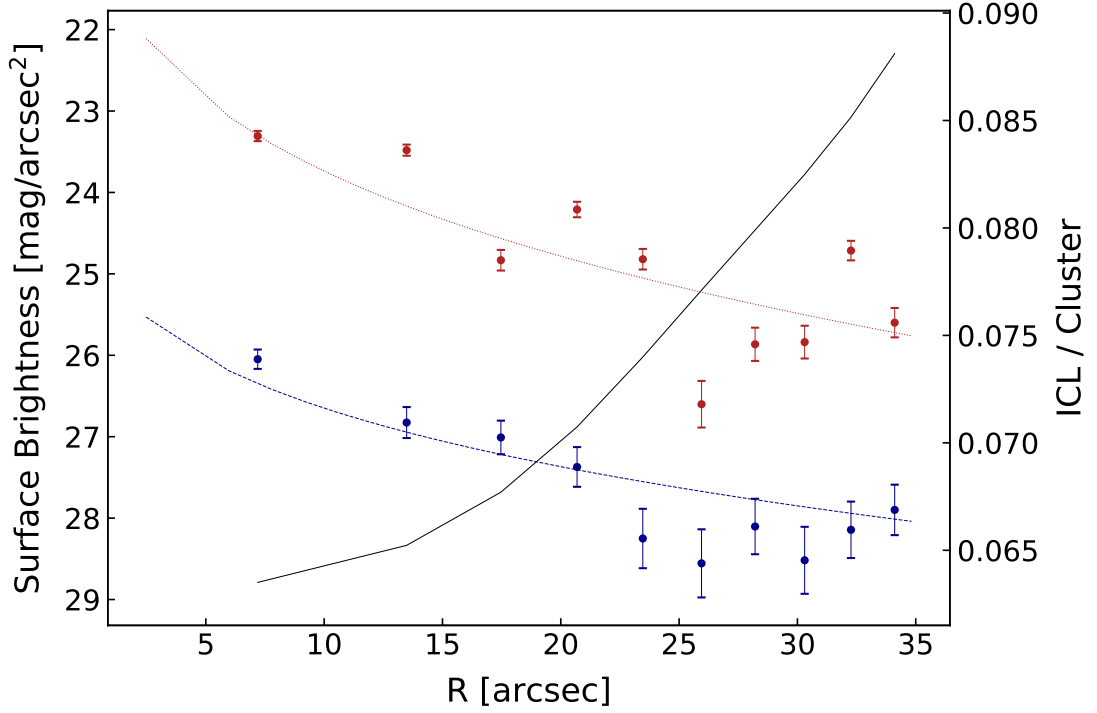


Figure 2.12: Radial surface brightness profile of the ICL (blue) and total cluster light (red), de Vaucouleurs profile fit to the ICL and cluster data are shown by the blue dashed and red dotted lines respectively. The dip seen at the outer edge of both the ICL and cluster surface brightness profiles is likely due to the initial masking process of stars and the CCD gap. The black solid line shows the ratio of the ICL to cluster light.

fraction ranges from as low as $\sim 6\%$ at the cluster centre where light is dominated by the BCG, up to $\sim 9\%$ towards the 200 kpc limits of this model. This trend is consistent with previous findings which have shown that the ICL fraction increases by around 2% in the inner regions of clusters ($\lesssim 200 - 300$ kpc) (Rudick et al., 2011; Morishita et al., 2017). Coincidentally, the surface brightness of the ICL drops sharply at the position of the giant arcs ($\sim 20''$). With a surface mass brightness of 26.63 and 27.71 mag/arcsec², internal and external of the radial arcs respectively, we see a drop of ~ 1 mag. Minimal straylight contamination is crucial for the identification of faint lensed sources in the cluster centre. Thus, low ICL fractions such as those found for here are beneficial when considering target clusters for JWST observations.

2.4.6 Mass Estimation

Dynamical Mass

For a virialized system, the dynamical mass is expected to scale as $M \propto \sigma^2 r_{50}$, where σ is calculated by considering only spectroscopically identified cluster members as detailed in Section 2.4.3, and we take the G³C value of $r_{50} = 0.66$ Mpc. The dynamical mass can then be estimated by:

$$\frac{M_{Dyn}}{M_{\odot}} = \frac{A}{G/M_{\odot}^{-1} km^2 s^{-2} Mpc} \left(\frac{\sigma}{km s^{-1}} \right)^2 \frac{r_{50}}{Mpc}, \quad (2.8)$$

where $G = 4.301 \times 10^{-9} M_{\odot} km^2 s^{-2} Mpc$ is the gravitational constant and A is a scaling factor calculated to be 6.2 (see Robotham et al., 2011, for more details). The dynamical mass of CLIO, calculated via this method is $M_{dyn} = (3.65 \pm 0.32) \times 10^{14} M_{\odot}$. This value is lower than the catalogue value of $5.62 \times 10^{14} M_{\odot}$ due to a combination of the refined velocity dispersion, and the significant increase in the number of cluster members, which acts to decrease the scaling factor A from 9.1 to 6.2. This method is biased towards a lower mass for a number of reasons; the velocity dispersion is measured along the line of sight only, and the intrinsic radius is likely to be larger than that of the projected radius due to a higher observed concentration of galaxies towards the cluster centre when viewed as a 2D distribution. Without a reliable r_{50} value, we find that this method cannot provide an accurate mass measurement. Instead, we employ various other techniques in order to obtain an estimate of the total cluster mass.

NFW Mass

As we have spectroscopy of almost 90 cluster members, we make use of our robust velocity dispersion measurement (Section 2.4.3) to estimate the total cluster mass. Assuming a spherical NFW mass distribution (as described in Section 2.4.3) of the

cluster, it is possible to obtain a total integrated mass. The mass enclosed within a given radius R is:

$$M(< R) = \int_0^R 4\pi r^2 \rho(r) dr, \quad (2.9)$$

where $\rho(r)$ is given by Equation 2.3. Taking the scale radius and characteristic density as described in Section 2.4.3, we apply $r_{200} = 1.68 \pm 0.03$ Mpc as the limiting radius to obtain a total halo mass of:

$$M(< r_{200}) = 4\pi r_s^3 \rho_s \left[\ln(1+c) - \frac{c}{1+c} \right] = \frac{800\pi}{3} r_{200}^3 \rho_c. \quad (2.10)$$

This is also known as the spherical overdensity mass. As our calculation for r_{200} depends only on the projected velocity dispersion and cluster redshift, the radial biases previously encountered (Section 2.4.3) can be avoided. This provides a mass estimate of $M_{200} = (4.49 \pm 0.25) \times 10^{14} M_\odot$. This method is, however, limited by the assumption that the cluster is well described by a spherical profile. This is unlikely to be accurate; even within the limited MUSE field it can be seen that there is an excess of large cluster member galaxies extending north-east out from the BCG. Despite this approximation, this method provides a good initial estimate for the total cluster mass.

Stellar Hydrodynamical Mass

The cluster mass of CLIO can be further investigated through the use of the Jeans equation. This relates spatial and velocity distributions of particles moving in spherical orbits, to the system's mass profile (Carlberg et al., 1997; Binney & Tremaine, 2008)

$$M(r) = -\frac{\sigma_r^2 r}{G} \left[\frac{d \ln(\sigma_r^2)}{d \ln(r)} + \frac{d \ln(v)}{d \ln(r)} + \beta \right]. \quad (2.11)$$

We will refer to this as the stellar hydrodynamical mass, where σ_r^2 is the radial velocity dispersion (taken from a fit to all spectroscopic cluster members with the system velocity removed), v is the radial number density profile, and $\beta = 1 - v_\theta^2/v_r^2$ is the anisotropy parameter. It is important to bear in mind that it is impossible to know the true value of β and the equation is not likely to provide physical results for highly radial orbits. From our investigations into the luminosity function (Section 2.4.4) and ICL fraction (Section 2.4.5) of the cluster, we find an excess of blue galaxies and low rates of ICL. Thus, we can assume that the cluster is still in an evolving state. This means that a significant fraction of cluster members are likely to have more radial, rather than isotropic orbits. However, if we make a simple assumption that the velocity ellipsoids follow isotropic orbits, then $\beta = 0$, and a mass of $(4.18 \pm 0.51) \times 10^{14} \text{ M}_\odot$ is found. This full mass profile can be seen in Figure 2.13. It is worth noting that this mass is only constrained within 0.4 Mpc ($\sim 0.25r_{200}$). With such high concentrations, a high fraction of the cluster mass is likely to be contained within its core, this value may initially seem like an overestimate based on our previous findings of $M_{200} = (4.49 \pm 0.25) \times 10^{14} \text{ M}_\odot$. However, if we reconsider the assumption that $\beta = 0$, the enclosed mass decreases down to $M(< 0.4\text{Mpc}) = 3.51 \times 10^{14} \text{ M}_\odot$ for $\beta = 1$. In reality, the true value of β is likely to fall somewhere between 0 and 1.

We estimate the dark matter halo mass fraction of the cluster by comparing the cluster mass, with that of the stellar masses calculated in Section 2.4.2. By adopting the stellar hydrodynamical mass calculated in this section we find a dark matter halo mass fraction of 91%. Comparisons against the dynamical (2.4.6) and NFW mass (2.4.6), provide estimates of 88% and 90% respectively.

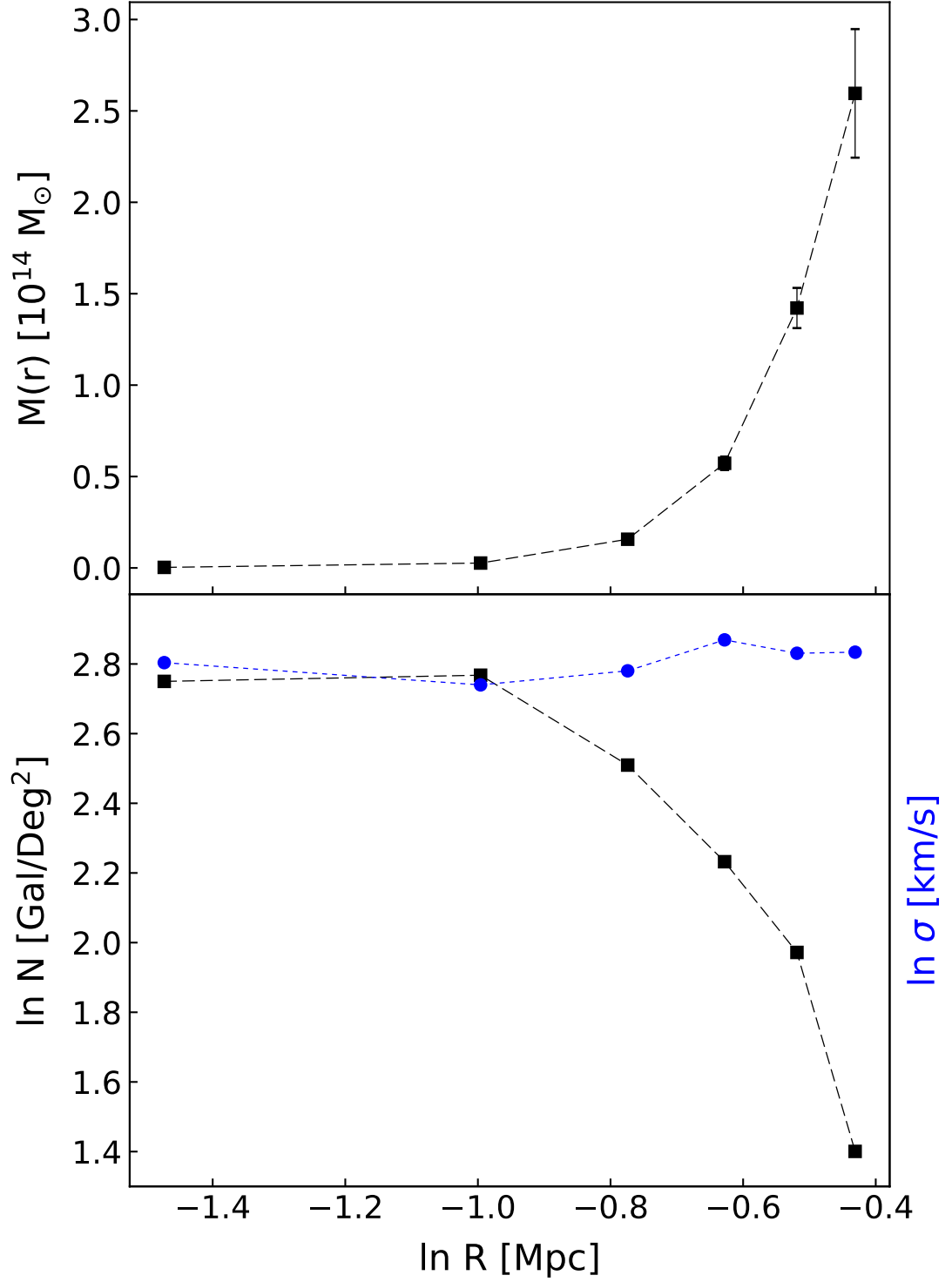


Figure 2.13: Top: Shows the radial mass profile of CLIO calculated via Equation 2.11 with a total mass estimate of $(4.18 \pm 0.51) \times 10^{14} M_{\odot}$. Bottom: Blue circles represent the natural logarithm ($\ln$) of the radial velocity dispersion (σ_r^2) in km s^{-1} , while black squares are the natural logarithm of the radial number density of cluster members (v) in units of galaxies per square degree.

2.4.7 Preliminary Lensing Models

We attempt to locate potential multiply imaged galaxies in order to build a robust strong-lensing model. Initially, we search for galaxies that lie close together in colour-redshift space, where we find 14 potential multiple-image groups consisting of a total of 43 individual images. Further investigation is then performed by stacking the spectra of each galaxy in the group to identify shared spectral features. Although a number of these did show promise, upon further investigation into the spatial locations of the galaxies, we found that none of them were reliable enough to be used in the initial modelling.

We identified multiple lensing arclets within the optical imaging, and made efforts to extract quality spectra from the MUSE datacube. We find two sets of arclets at roughly the same radial distance from the cluster centre (lower left and upper right of the cluster core as seen by points A1 and A2 respectively in Figure 2.4) indicating the source galaxies are likely situated within a similar redshift range. At the lower left we find an extended arclet; its spectrum presents no strong emission or absorption features, but we fit suspected C III] 1909Å, C IV 1550Å and Mg II 2798Å features to find a preliminary redshift of $z = 2.37$. The upper right arc is less luminous and appears to have multiple components, indicating this is a fold arc with a single source, or individual images of two galaxies situated in close proximity in the source plane. Again, the spectra of these components show no strong features, but we fit a preliminary redshift of $z = 2.18$ to both of them. There is a small shift between fits of the two components, indicating that the images may be from separate, but closely situated, source galaxies. However more accurate spectra are required to verify this. The redshifts of these arclets, although of lower quality ($Q = 2$) are included in our redshift catalogue, as they have been used to constrain our preliminary lensing models.

Light-Traces-Mass modelling

Given that no obvious multiple-imaged galaxies were detected in the data, a first, rough strong-lensing strength estimate for the cluster was obtained with the automated Light-Traces-Mass code (LTM; Zitrin et al., 2012b). This method relies on the simple assumption that light traces both the stellar and roughly the dark mass within the cluster. The LTM model is particularly applicable here as it can be self-calibrated on other lensing clusters with known images. This yields a good initial estimate for the mass distribution, even without multiple image inputs (Zitrin et al., 2012b). While the mass distribution and locations of critical curves have been found to be well constrained by the cluster light distribution, the mass profile remains uncertain. Without available multiple images, extrapolation of the mass profile out to M_{200} is unreliable. Thus, the most secure method of mass estimation is to compare the Einstein radii to a distribution of clusters. Using a sample of carefully analysed clusters from the GMBCG catalogue (Hao et al., 2010), Zitrin et al. developed a LTM scaling relation that predicts the location of the critical curves from the luminosity distribution of cluster members, which in turn can be used to estimate M_{200} and a corresponding uncertainty.

Due to the lack of multiple images, we initially use the self-calibrating LTM model (hereafter, LTMv1). For this, we use the FORS2 red sequence member galaxy list, which includes both spectroscopic and colour-colour identified member galaxies. This method yields a relatively small effective Einstein radius of $8.4'' \pm 20\%$, enclosing a mass of $2.02 \times 10^{13} M_{\odot}$. The small Einstein radius is in agreement with the lack of multiply imaged galaxies identified. Comparing to Weak Lensing results from the CLASH survey (Umetsu et al., 2016), this Einstein radius typically corresponds to clusters with M_{200} of about few $10^{14} M_{\odot}$.

In addition, we construct a secondary model from the Zitrin et al. (2012b) automated method (we refer to this model as LTMv2). This time, the critical

curves are scaled by hand to match the radius in which the arcs are seen, providing an effective upper limit on the Einstein radius and thus, cluster mass. This model yields an effective Einstein radius of $r_E \sim 15''$ enclosing a mass of $\sim 4.5 \times 10^{13} M_\odot$. Following the Umetsu results mentioned above, this radius typically corresponds to a higher mass cluster than our first model estimate, yielding an upper limit on the total mass of $M_{200} \sim 10^{15} M_\odot$.

Weak & Strong Lensing Analysis Package

We perform complimentary lensing mass model reconstruction using the Weak & Strong Lensing Analysis Package (WSLAP+; Diego et al., 2005, 2016). WSLAP+ is a free-form method used to model gravitational lenses using a combination of weak and strong lensing data. The mass in the lens plane is modelled as a combination of a diffuse and a compact component. The diffuse component is a superposition of Gaussian functions located at a distribution of regular or adaptive grid points. The compact mass accounts for the baryonic and dark components associated to the elliptical-type member galaxies selected from the cluster red sequence. The distribution of mass is assumed to trace the light of these compact galaxy components. A detailed description of the code and the different improvements implemented can be found in the papers Diego et al. (2005), Diego et al. (2007), Sendra et al. (2014) and Diego et al. (2016).

We employ the spatial distribution of cluster member galaxies in combination with arclet positions, their extent, and redshifts as constraints to derive a strong lensing mass model using the WSLAP+ package. The arclets are mapped in their entirety (not just their centroids) and included as constraints. Instead of assuming the centroid positions of the arclets (1 point for the arc in the lower-left side of the field of view at $z_1 = 2.37$, and 2 points for the two arclets in the upper-right side of the field of view at $z_2 = 2.18$) as is usually done in lensing reconstruction methods,

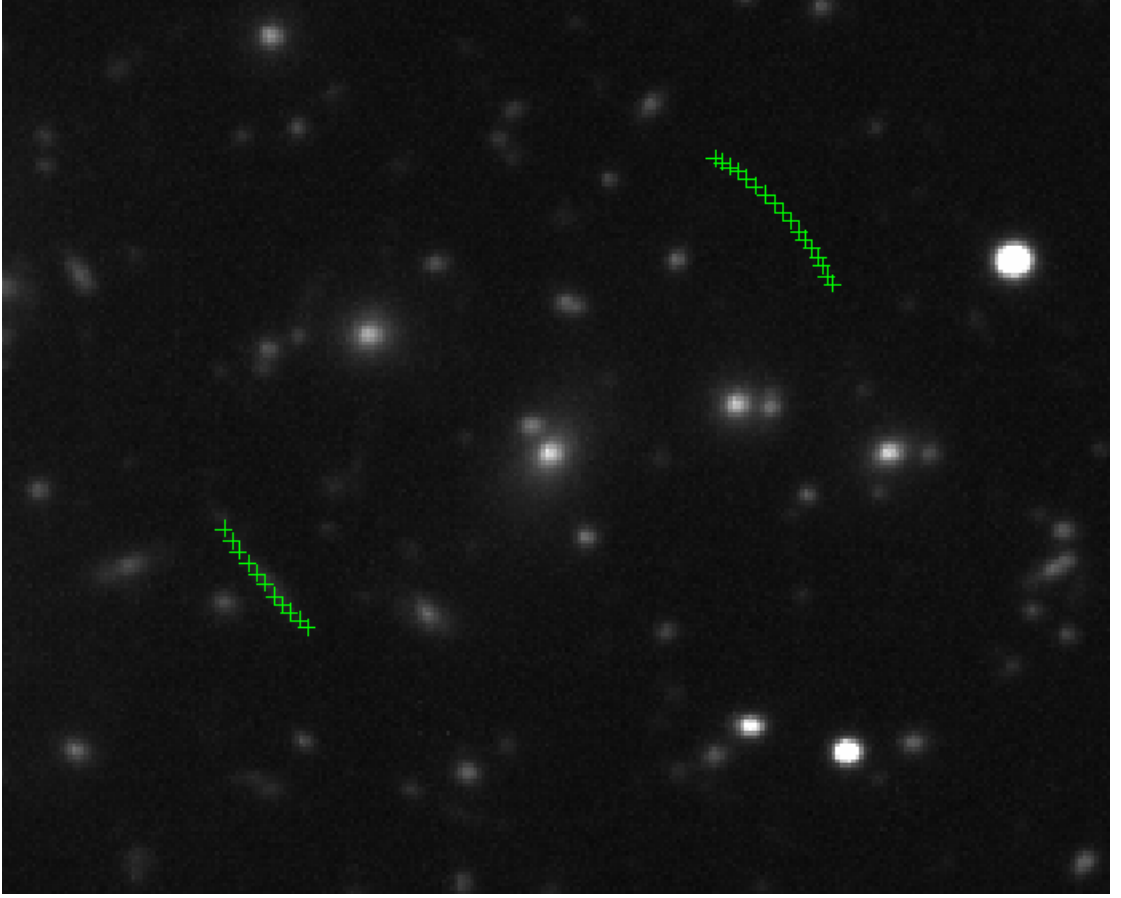


Figure 2.14: Positions of the A1 (11) and A2 (17) arclet constraints used in WSLAP+ modelling. Points are overlaid on FORS2 r -band image.

we consider 11, and 17 points for the arcs at $z_s = 2.37$ and $z_s = 2.18$ respectively. A list of central arc positions, along with an illustration of the points used, can be found in Table 2.4 and Figure 2.14. These points are roughly equally spaced with a separation of $\approx 0.7''$ between them. The points do not correspond to particular features in the observed arcs but rather they trace the shape and extension of the arcs. The algorithm exploits the extension of the arclets by requiring that the lens model *focuses* the extended arcs into small compact regions in the source plane. This approach is very useful when the number of constraints is scarce but there are giant arcs in the lens plane.

Also, incorporating the member galaxies in the lens model acts as an *anchor*, constraining the range of possible solutions and reducing the risk of a bias due to the

Table 2.4: Table of central positions and redshifts for arclet constraints used in the WSLAP+ modelling.

ARC	ID	z	R.A [deg]	DEC. [deg]
A1	271	2.37	130.5960377	1.6383164
A2.1	153	2.18	130.5881129	1.6458672
A2.2	180	2.18	130.5862754	1.6438599

minimization being performed in the source plane. The algorithm determines the optimal distribution of mass by minimizing the lens equation under the additional constraint that the mass in each cell must be positive. For this particular cluster, we use a regular configuration with 8×8 grid points (or Gaussians) to fit the diffuse component. All member galaxies are assumed to have the same mass-to-light ratio which is determined as part of the optimization process.

This preliminary model, which can be seen in Figure 2.15, provides no further constraints at this time as no counterimages are identified using our current data. Without weak lensing analysis, or additional strongly lensed systems, the WSLAP+ mass model reconstruction only constrains the central part of the galaxy cluster, out to a radius of ~ 35 arcseconds. We extrapolate the integrated mass profile out to r_{200} by fitting a NFW to estimate a total cluster mass. While fitting well to the density profile within the central ~ 35 arcsec, even slight variations in the concentration of the NFW profile provide vastly different results when extrapolated out to r_{200} . To provide the most robust estimate, we use our previously calculated concentration (Section 2.4.3) of 7.61 to obtain a total cluster mass of $\sim 6 \times 10^{14} M_{\odot}$. It is worth noting that strong-lensing-only extrapolations tend to overestimate total cluster mass, since clusters are not axially symmetric and often present complex substructure.

Through the use of observed lensing arcs, we are only able to constrain the

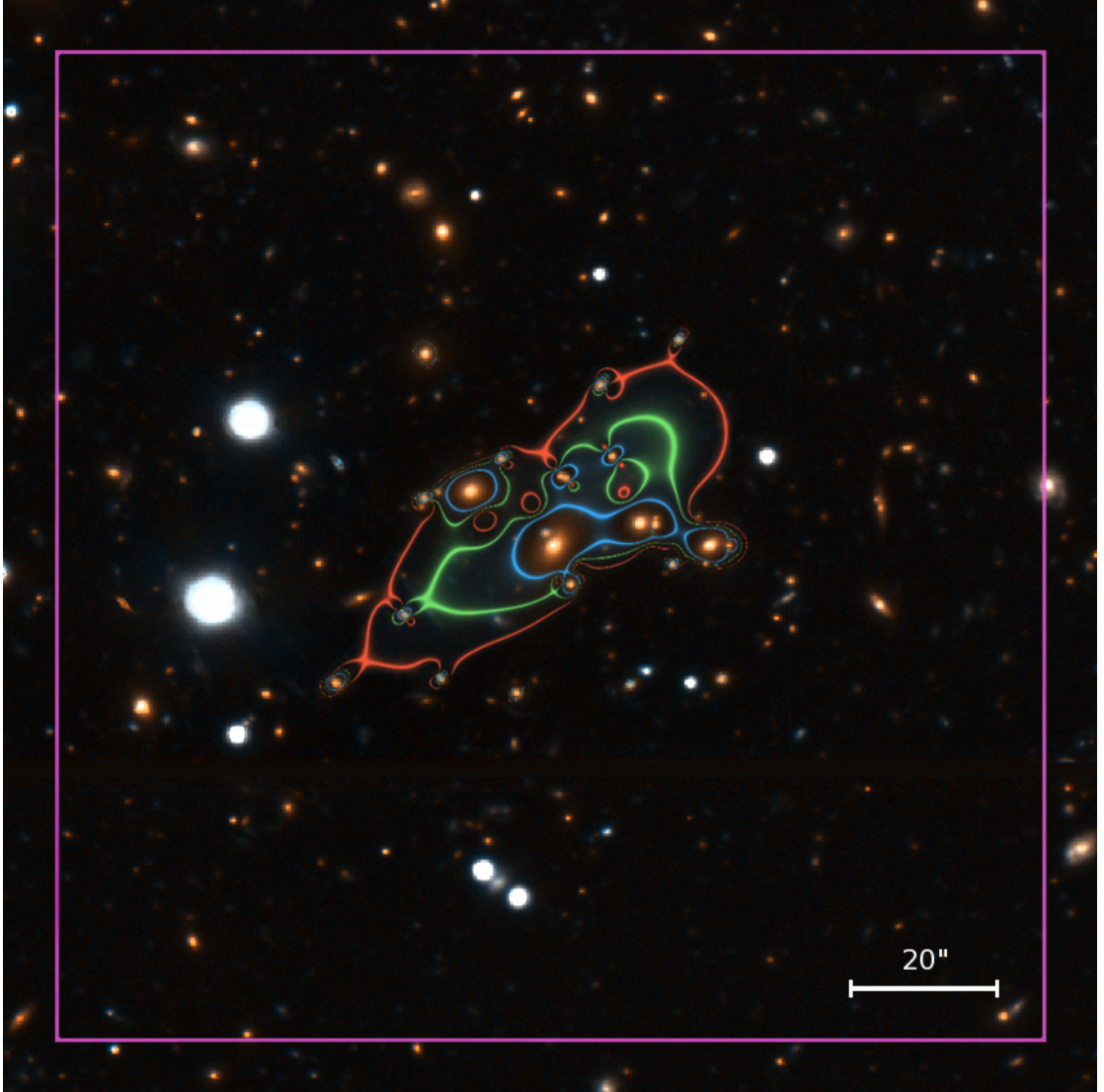


Figure 2.15: False colour image constructed with g and r -band FORS2 data showing the central region of the CLIO cluster. Critical curves for the preliminary lensing model are shown in blue, green and red. The blue line shows the tangential critical curve for a redshift of $z = 1.2$, where there is a peak in the redshift distribution. Green, represents the critical curve for the estimated arclet redshift of $z = 2.2$. Finally, the red line is the $z = 6$ critical curve. The JWST NIRCам Module A FoV is overlaid as the magenta box.

mass enclosed within the Einstein radius of the lens, and not the full mass profile. While the LTM method constructs a projected mass distribution based on the observed light, WSLAP+ does not make the same assumption. Thus, the density profiles of the models are intrinsically different, even if the integrated mass within the Einstein radius may agree. In Figure 2.16, we show that the mass profiles calibrated using arc positions (LTMv2 and WSLAP+) are consistent within the Einstein radius of the lens. However, it can be seen that these profiles differ significantly beyond 15 arcsec, and hence extrapolations out to larger radii can result in significant differences in calculated enclosed masses. The addition of new arcs at larger radial distances, or weak lensing data will allow further constraints on the density profiles to reduce uncertainty.

The extension of the critical curve predicted from our model (at $z \sim 3$) is able to magnify an area smaller, but still comparable, to that of the powerful lenses. Since (to first order) the area above a given magnification in the source plane is proportional to the same area in the image plane divided by the magnification, CLIO is able to magnify (above a given magnification) about half the area when compared with the most powerful lenses. This is beneficial for JWST NIRCам observations due to its limited field of view. Given the fact that the main factor determining the number of observed high redshift galaxies around a lens is cosmic variance (i.e, the number of high redshift galaxies that fall in the footprint of the high magnification region in the source plane), it would not be surprising if high redshift galaxies are found behind CLIO when observed with powerful IR telescopes like JWST.

2.5 Summary

We have presented the first measurements and detailed study of the compact galaxy cluster CLIO. We perform standard data reduction procedures on dual-band

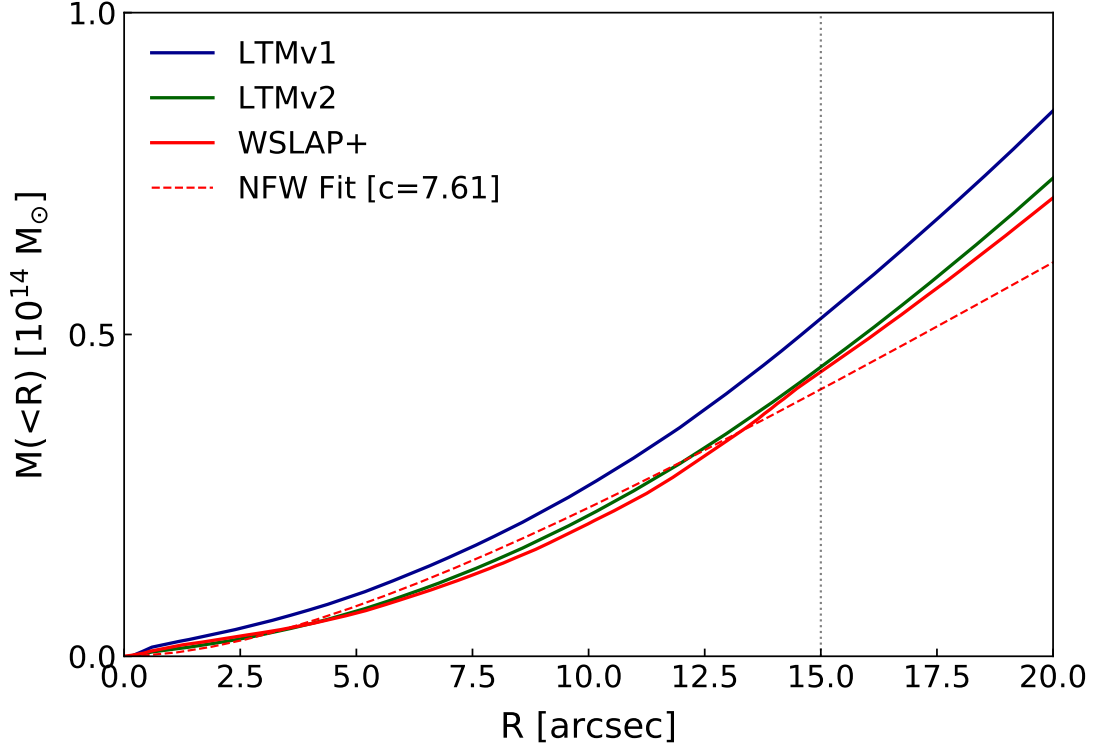


Figure 2.16: Enclosed mass profiles derived from both LTM, and WSLAP+ lensing models. The blue line shows the self-calibrated LTMv1 model which provides an Einstein radius of $8.4''$, which encloses a mass of $1.29 \times 10^{13} M_{\odot}$. The green line shows the LTMv2 model, calibrated to the observed lensing arcs, providing an Einstein Radius of $15''$ (grey dotted line), enclosing a mass of $4.33 \times 10^{13} M_{\odot}$. In red we see that the WSLAP+ model, also calibrated to the observed arcs, provides a consistent mass profile within the Einstein radius, enclosing a mass of $4.42 \times 10^{13} M_{\odot}$. The red dashed line shows the NFW profile used for the WSLAP+ mass estimate. It can be seen that while the models agree well within the Einstein radius, they deviate significantly when extended to larger radii.

FORS2 optical imaging and multiple-channel IRAC imaging. We perform object detection on the r -band image in order to create spatial profiles for extraction of weighted spectra from the MUSE IFU datacube. Redshift analysis is performed using a customised version of the cross correlation MARZ code, results are checked against findings from python based emission line detection packaged MUSELET. We identify 89 cluster members at redshifts $z = 0.42 \pm 0.01$ and a further 75 background objects out to $z = 6.49$.

Photometry is measured for all detected objects in the FORS2 field and we find corresponding galaxies in the IRAC data. After applying K-corrections and considering extinction effects we calculate $(g-r)$ and $(3.6\mu m-4.5\mu m)$ colours. We then use a colour to mass-to-light relation to estimate stellar masses of all spectroscopically identified cluster members. Additionally, we use galaxy colours and HSC photometric redshifts to measure the cluster red sequence and search for additional cluster candidates outside of the spectroscopically covered field, yielding a total of 198 additional galaxies.

We investigate cluster properties to update initial G³C estimates. Using the 89 spectroscopically identified cluster members, we calculate a velocity dispersion of $\sigma = (619 \pm 11) \text{ km s}^{-1}$ using the robust gapper estimator. We use an iterative process to find the projected cluster centre is located at the BCG, and is not sensitive to interlopers.

There is a radial bias induced by the limited MUSE coverage, so we adopt a velocity dispersion based estimator for r_{200} . We calculate a concentration value of $c = 7.61 \pm 0.43$ by fitting a NFW profile to the clusters projected number density. This high concentration confirms initial assumptions made during cluster selection. Additionally, a concentration value such as this is thought to explain the presence of the strong lensing features observed, and may be indicative of a triaxial halo.

Through the investigation of the luminosity function, we find an excess of

faint blue galaxies when compared to lower redshift samples. As indicated by the Butcher-Oemler effect, the fraction of red, quenched galaxies increases with a clusters age, thus suggesting that the CLIO cluster is still in an evolutionary state. Further, we investigate the ICL fraction of CLIO through parametric profile fitting using the GALFIT software package. Through the analysis of object-subtracted residual images, we find an ICL fraction of $7.21 \pm 1.53\%$, which is in the lower range of ICL measurements at similar redshifts. This low ICL fraction is ideal to maximise the detection of faint lensed sources. Further, it suggests that the ICL in CLIO is still in development, making it an interesting candidate for JWST lensing studies.

We find that due to the high concentration of the cluster, any mass estimates based on radial measurements prove unreliable. Instead we adopt two separate estimates based on velocity dispersion. We first assume the mass is distributed as a NFW profile and choose the enclosing radius as r_{200} to achieve a purely velocity-dispersion based estimation of $M_{200} = (4.49 \pm 0.25) \times 10^{14} M_{\odot}$. Secondly, we apply Jeans analysis to estimate the stellar hydrodynamical mass contained within 0.4 Mpc to be between $M(< 0.4\text{Mpc}) = (3.51 \pm 0.39) \times 10^{14} M_{\odot}$ and $(4.18 \pm 0.51) \times 10^{14} M_{\odot}$, for $\beta = 1$ and 0 respectively.

Finally, analysis of galaxy spectra provides a number of potential multiply imaged galaxy candidates, but we cannot confirm these with the existing data. Despite this, we use the automated Light-Traces-Mass and WSLAP+ methods to provide a rough strong-lensing estimate. With both models calibrated to the positions of the lensing arcs, we constrain the Einstein radius to be at $r_E \sim 15''$. LTM and WSLAP+ models calibrated in this way provide consistent mass profiles within r_E . They are however unreliable when extrapolated to larger radial distances. For the LTM model, we use a scaling relation to find an upper limit on the total cluster mass of $M_{200} \sim 10^{15} M_{\odot}$. We fit a NFW to the WSLAP+ mass profile

within $15''$ to find a mass of $M_{200} \approx 6 \times 10^{14} M_{\odot}$.

In summary, CLIO is an excellent cluster for future follow up work. It is a highly concentrated massive system that already has, with modest MUSE spectroscopy, several high- z lensing candidates. More detailed study will reveal properties of its dark matter halo, including measuring its profile in detail and quantifying its sub-halos. Because of its high concentration and low ICL, it is an ideal target for JWST observations and will be part of the Webb Median Deep Fields GTO effort to study the early Universe.

Chapter 3

AutoSpec: Automated Spectral Extraction Software

This Chapter explores the design and implementation of a novel approach for source identification and extraction from within integral field unit (IFU) data. Instead of using pre-defined apertures or segmentation regions for spectral extraction, we utilise a simple cross-correlation algorithm coupled with continuum subtraction in order to isolate and deblend sources. This work is published in full in Griffiths & Conselice (2018) and contributes to the work presented in Leisawitz et al. (2019).

3.1 Introduction

Spectroscopic analysis of galaxies provides a wealth of information not available from photometric methods. Most of the advances in astrophysics over the past 100 years have come about due in part to spectroscopy coupled with imaging, and this shows no sign of abating over the next few decades. Insights provided by spectroscopy include, but are not limited to: radial velocities and redshifts, chemical abundances, internal motions of objects, and the identification of objects along the line-of-sight which can only be seen in absorption, such as Lyman-alpha clouds.

The analysis of a galaxy’s content from absorption and emission lines can thus provide an insight into its formation and evolutionary history. The benefits of spectroscopy are ever more prevalent with the introduction of integral field units (IFUs) that can simultaneously obtain spectra over large regions of the sky. IFUs have traditionally been used to determine the internal properties of galaxies, with each optical fibre probing a different physical location within a galaxy. However, new generation IFUs with large fields of view can now be used to probe galaxy clusters or ‘blank’ fields where in principle, many galaxies are observed within a single IFU pointing.

In current and upcoming eras of astronomy, there is a wealth of information that multi-object IFU observations can provide within these dense, or blank field areas of the Universe. This includes finding galaxies that cannot be seen in the deepest continuum optical imaging (Bacon et al., 2017), as well as in the study of galaxy clusters (e.g., Griffiths et al., 2018; Mahler et al., 2018). Not only does an IFU give information on the radial velocity, and thus membership and physical properties of member galaxies; it also provides information on any background lensed systems (Chapter 2). For example, the accurate identification of multiply-imaged galaxies through spectroscopic redshifts provides critical constraints for lensing models. Currently, IFUs are the best, most efficient way to get a complete sample of lensed galaxy redshifts.

An ever increasing amount of scientific research is being conducted with the aid of IFUs such as the multi-unit spectroscopic explorer (MUSE; Bacon et al., 2010) and the Gemini Multi-object Spectrograph (GMOS; Hook et al., 2004), as well as plans for future instruments on the James Webb Space Telescope (JWST) and the Extremely Large Telescope (ELT). With this progress comes the daunting and time consuming process of extracting useful information from the large datacube files produced.

For astronomical images this process is well established; software such as SExtractor (Bertin & Arnouts, 1996) is widely used to detect, measure, and classify sources through the creation of photometric catalogues. However, for the analogous process of extracting spectra from three dimensional data, the optimal methodology at this time remains unclear and is typically carried out using various unrefined approaches.

Many spectroscopic IFU studies are based on the photometric pre-selection of objects, in which catalogues derived from ancillary imaging data, or taken from previous studies, are used as a basis of spectral extractions. An alternative comes in the form of software such as the Line Source Detection and Cataloging Tool¹ (LSDCAT; Herenz & Wisotzki, 2017) and the MUSE Line Emission Tracker² (MUSELET; Bacon et al., 2016). These software packages employ computational techniques to perform blind searches of a datacube in order to identify emission lines. In fact, a combination of photometric pre-selection and blind searches has been found to be favourable (e.g., Bacon et al., 2017; Griffiths et al., 2018; Mahler et al., 2018) to produce source catalogues for spectral extraction. Unfortunately, the optimal method for obtaining one dimensional spectra from an IFU datacube still remains unclear.

The simplest approach is to extract spectra based on fixed apertures, such as is commonly done when measuring galaxy photometry and implemented through source extraction methods and tools such as SExtractor (e.g., Bina et al., 2016; Karman et al., 2017). An evident drawback to this method is encountered when dealing with more complex sources such as lensing arcs and extended galaxies or emission regions.

¹LSDCAT available at <https://bitbucket.org/Knusp2000/lscat>

²MUSELET is part of MPDAF, documentation available at <http://mpdaf.readthedocs.io/en/latest/muselet.html>

To circumvent some of these issues, an object’s morphology can be used when defining spectral extraction regions. IFU studies of galaxy clusters such as (Chapter 2) and Mahler et al. (2018) implement the use of SExtractor segmentation maps derived from deep imaging data as a basis of weighted spectral extraction. The work recently carried out on MUSE observations of the Hubble Ultra Deep Field (Bacon et al., 2017) also follows similar extraction methods. It is however, not difficult to imagine situations where this may not be entirely applicable, such as the case where an object has extended emission in wavelength ranges not covered by the available imaging.

Here, we argue that an abundance of spectral information is being overlooked in existing extraction techniques which typically use predefined spatial regions (e.g. apertures or segmentation maps). We present a new method for the identification of the spatial extent of objects directly from IFU datacubes without the need for ancillary imaging or prior knowledge of the sources. The combination of established aperture and segmentation region extraction methods with a simple, but novel custom designed cross-correlation algorithm, can lead to an improvement in spectral signal-to-noise as well as the successful isolation of sources from neighbouring contaminants.

We structure this Chapter in two main parts; firstly, in Section 3.2 we present our novel technique for the optimal spatial identification of sources directly from a datacube, utilising the wealth of information available. In Section 3.3 we provide an overview of our Python based software package AUTOSPEC, which implements these techniques, along with existing methods for the fast, automated extraction of one dimensional object spectra. We conclude by showing the versatility of the techniques described in this Chapter by exploring alternative uses beyond its original design goals.

3.2 Optimal Source Identification

With typical spectral extractions based on circular apertures, or an object's morphology in a particular photometric band, a wealth of information is available within an IFU datacube which is entirely overlooked. Thus, current methods are not ideally suited to spatially identify a source for the purpose of extracting its spectrum. Furthermore, obtaining a sources spectrum from an IFU datacube is a complex process, not to mention the computing power required to handle such large file sizes. With no established methods, we are left to ask questions such as; which spectral pixels (spaxels) correspond to the source, and how best to combine and weight them in order to obtain an optimal 1D spectrum? To answer these questions we present here, a simple but novel technique, combining cross-correlation with continuum extraction to identify and isolate astronomical sources directly from within a datacube itself.

3.2.1 Cross-correlation

Our cross-correlation technique is designed to optimally locate a source, directly from within a datacube. In order to calculate the correlation weight, an initial reference spectrum is required. In principle, a spectral template could be used if there is prior knowledge of a sources properties, such as redshift and spectral type. This is however often not the case, so a reference can be obtained via established methods where object masking is best defined either by a circular aperture or morphologically based segmentation region. The first step is to create a truncated cube (subcube) around the source in order to reduce both the processing power and computation time required. From the subcube a spectrum can be obtained via the optimal extraction algorithm (Horne, 1986);

$$f(\lambda) = \frac{\sum_x M_x W_x (D_{x,\lambda} - S_\lambda) / V_{x,\lambda}}{\sum_x M_x W_x^2 / V_{x,\lambda}} \quad (3.1)$$

where $f(\lambda)$ is the resultant flux. M is the object mask, D and V are data and variance cubes respectively while S is the sky spectrum. The ideal initial weight image, W , is source dependent and can take the form of ancillary broad or narrow band imaging. However, if this is not available a ‘white-light’ image created by flattening the datacube along the spectral axis is often sufficient.

Assuming the source is not extended such that Doppler shift gradients are negligible, we employ cross-correlation techniques with zero spectral lag. This provides a measure of similarity between the reference spectrum and the spectrum of each spaxel within the subcube. A two-dimensional measure of the cross-correlation strength, $cc(x, y)$ is obtained via the equation;

$$cc(x, y) = f_{\lambda} \star F_{\lambda}(x, y) \quad (3.2)$$

where $cc(x, y)$ is the cross-correlation strength map, f_{λ} is the reference spectrum and $F_{\lambda}(x, y)$ is the subcube spaxels. This cross-correlation technique yields a strength map which details by what degree each spaxel within the subcube correspond to the reference spectrum. A higher value is given to spaxels in which the two spectra are similar (i.e. spaxels which correspond to the source), while lower values are given where spaxels show fewer, or no similarities (i.e. background sky, other objects or contaminants). This method effectively negates any selection effects of morphological analysis via photometrically defined segmentation regions or apertures, while simultaneously providing a weighting scheme for secondary spectral extraction. Further extractions can be performed via Equation 3.1, using the correlation strength map as a weighting scheme, W . In theory, if the source is sufficiently isolated this technique could be applied without any additional masking; however for general cases we have found masking helps to suppress noise and maintain flux conservation. In principle, this weighted extraction technique is a spectroscopic analogue of the photometric methods presented in Naylor (1998).

The successfulness of this technique is however limited by the initial reference spectrum used. If a cross-correlation is performed with a reference spectrum that is not a good representation of the object, this technique will provide a less useful map. The main factors which can negatively influence results are noise, and ill-defined masks or initial weight schemes. Sources of noise such as neighbouring contaminants that are not properly masked out can heavily bias the reference spectrum. For faint objects, where morphologies can not be sufficiently approximated from the white-light or supplementary imaging, we find appropriately sized apertures are best for initial extractions. For more complex sources such as lensing arcs or extended galaxies, morphologically based extractions prove to be most efficient. For sources that are not sufficiently isolated from neighbouring objects, we find that the resultant cross-correlation maps can become heavily biased and unreliable, especially when the target source is fainter than nearby contaminants.

3.2.2 Isolating and deblending sources

As previously mentioned, our cross-correlation technique alone is not sufficient to successfully isolate sources from neighbouring objects. This issue presents itself when a contaminating object has a similar continuum shape to that of the target source, greatly biasing the resulting cross-correlation strength maps obtained. When this is the case, a continuum subtraction needs to be performed on both the reference spectrum, and each spaxel within the subcube before the correlation strength is measured. This can successfully negate any continuum-induced bias to the resultant correlation strength maps obtained, leaving only the spectral emission and absorption features of the source to contribute.

To obtain an estimate of the continuum, we perform a simple fifth-degree polynomial fit. We use this method for both its speed and simplicity as it is performed on both the reference spectrum, and on each spaxel within the subcube

individually. A more robust estimation technique could be employed to include iterative processes and outlier removal, but this would become computationally expensive. Alternatively, a continuum could be estimated from only the reference spectrum and applied to the full subcube, however during our testing we found the resulting strength maps were not as reliable when produced via this method.

We find that for objects that are not sufficiently isolated, a combination of cross-correlation and continuum subtraction provides optimised spatial identification of sources within the datacube while simultaneously deblending the source from contaminating objects. A visual example of the effectiveness of this method is shown in Figure 3.1. To further improve spectral quality, it is feasible to extend this method to be performed iteratively, in which a spectrum derived in step i , can be implemented as reference for iteration $i + 1$ in order to obtain more refined cross-correlation strength maps.

3.2.3 Signal-to-noise

To provide some quantification of this method, we compare the signal-to-noise of traditional morphologically and aperture derived spectra to those extracted via our techniques described here. To investigate the signal-to-noise of the spectra, we first select various source types with known redshifts. We extract spectra via an appropriately-sized aperture as well as weighted extractions with masks defined by segmentation regions. We weight these extractions using both the MUSE white-light, and deep g-band imaging. Further, when appropriate we perform additional extractions based on PSF (for stellar spectra) and narrow-band (for high redshift sources) weighting schemes. The narrow-band image is constructed from the datacube, with a width of $100\text{\AA}$ and centred on the Ly- α emission line.

From these initial extractions, we take the best spectra for each object and use it as a reference for our cross-correlation methods. Extracting a spectrum

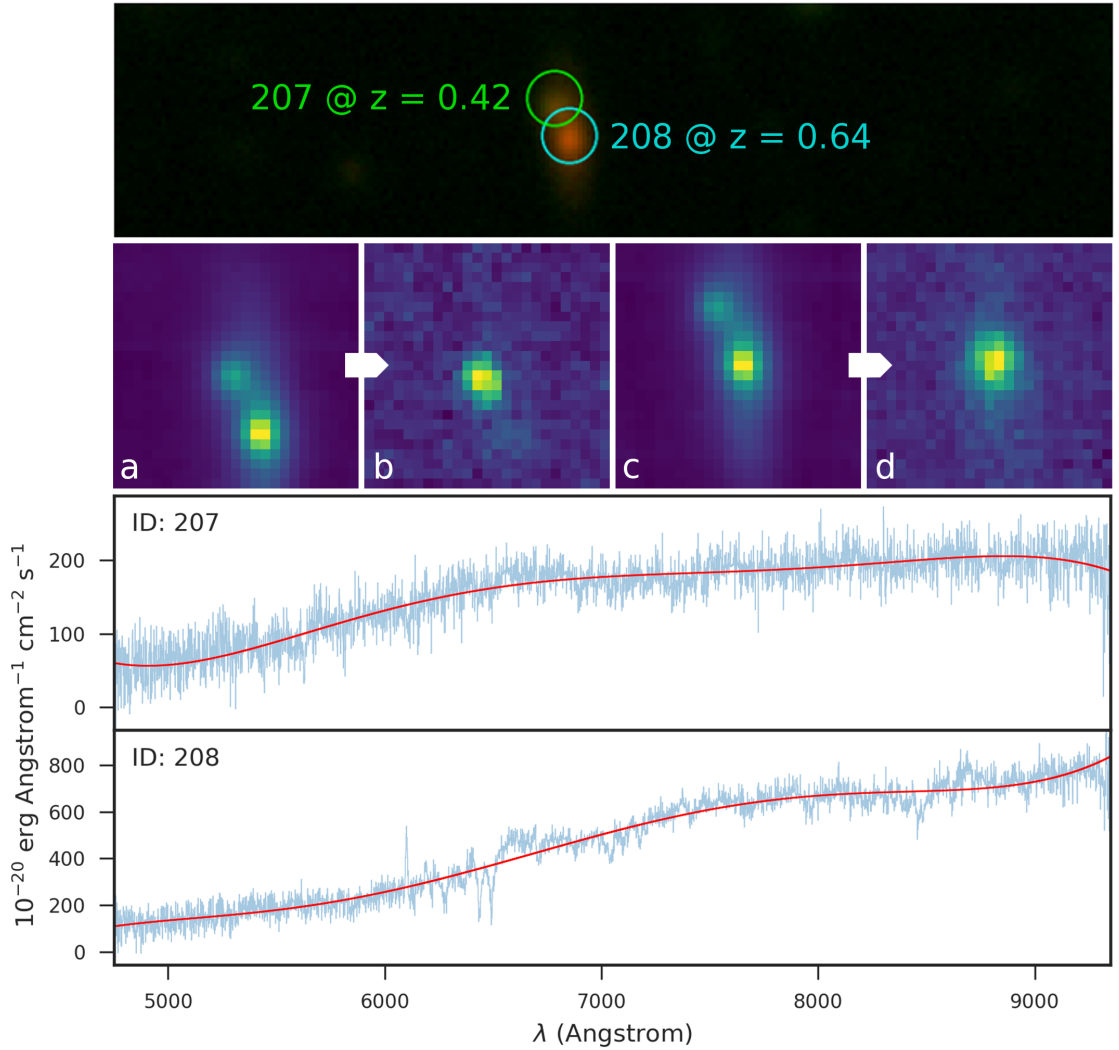


Figure 3.1: We show here the effectiveness of continuum subtraction for a pair of galaxies in close proximity within an observation. Top shows the false colour image with source positions overlaid. Bottom two panels show the reference spectrum of each source in blue, and in red we show the continuum estimated using a five degree polynomial fit. Here it can be seen that even though the continuum of the two sources is different, the overall similarity will bias cross-correlation results when the two objects are in this close a proximity. The middle panel a and c show the cross-correlation map without the additional continuum subtraction step for source id 207 and 208 respectively. It can be seen in these images that the contaminating source is also picked up by our cross-correlation methods. b and c show the cross-correlation maps over the same spatial region, this time performed after the additional continuum subtraction routine. Through the comparison of a and b, or c and d, the strength of the cross-correlation algorithm, combined with continuum subtraction is shown to successfully identify a sources spatial distribution and isolate it from nearby contaminants.

both before, and after the additional continuum subtraction step. To estimate the signal-to-noise as a function of wavelength we fit a template spectrum to each of the spectra extracted. Template fitting is performed using the Python Spectroscopic Toolkit³ (PYSPECKIT; Ginsburg & Mirocha, 2011). PYSPECKIT finds the optimal shift and scaling for the given template to accurately match input spectra. We calculate signal-to-noise as a function of wavelength by dividing the shifted, scaled model by the square root of the original spectrum. We find this provides an accurate representation of the noise in order to compare the various extraction methods.

In Figure 3.2 we show the spectral signal-to-noise for an example source, an extended lensing arc with nearby foreground contamination (this object can also be seen in Figure 3.5.2). White-light and deep imaging weighted spectra show an improved signal-to-noise over a circular aperture extraction as can be expected for an extended object. Through the use of our cross-correlation derived strength map alone, we find approximately the same results as imaging-weighted extractions. Including the extra continuum subtraction step, we see $\sim 20\%$ improvement in the spectral signal-to-noise over the next best method. This improvement in signal-to-noise shows that our techniques are able to successfully isolate the source from the foreground contamination, and provide a sufficient weighting scheme for further spectral extraction. Improvements such as this are especially significant when dealing with faint and obscured galaxies, or looking to obtain accurate spectral line measurements.

We show the results for other object types investigated in Figure 3.3. Here, we take the median signal-to-noise value over the entire spectral range to more easily represent the data. We further normalise the signal-to-noise measurements such that

³PYSPECKIT available at <https://github.com/pyspeckit/pyspeckit> and <https://bitbucket.org/pyspeckit/pyspeckit>

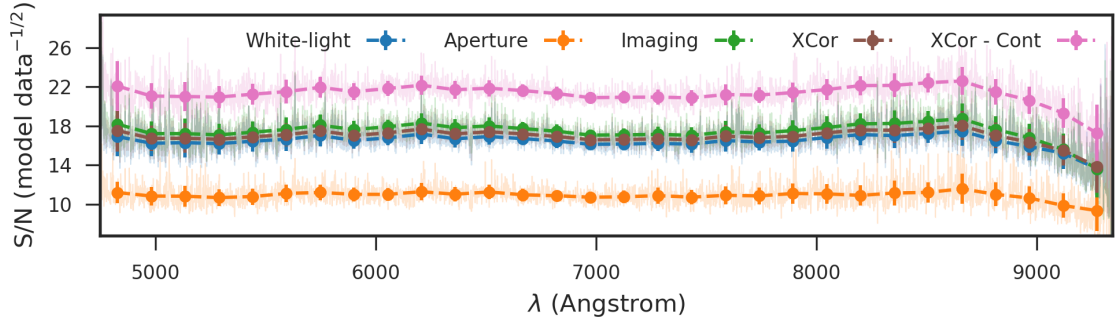


Figure 3.2: We show here the improvement in spectral signal-to-noise through the use of our cross-correlation strength map for an extended lensing arc with various sources of foreground contamination. Additionally, we show the averaged signal-to-noise of this object in Figure 3.3 as well as the white-light image and cross-correlation strength map in Figure 3.5.2. In blue and green, we show the signal-to-noise of a spectrum extraction defined via a segmentation region, weighted by the MUSE white-light image and deep g-band imaging respectively. Orange shows the signal-to-noise of a spectrum extracted via a circular aperture region while brown and pink show cross-correlation weighted extractions (with and without the additional continuum subtraction steps respectively). The signal-to-noise is represented as a function of wavelength across the entire range of the IFU datacube, while the dots show the mean data value for bins of $\sim 150\text{\AA}$. We show that for this object, our cross-correlation technique combined with continuum subtraction improves the signal-to-noise by $\sim 20\%$ from the next best extraction method (a deep imaging weighted extraction).

the peak value for each source is equal to one. These examples show that for well defined objects such as stars and low redshift galaxies, extractions based on our cross-correlation strength maps provide only a marginal improvement over traditional extraction techniques. However, for more complex sources such as unresolved high redshift galaxies and extended lensing arcs, the implementation of our techniques produces a clear increase in the resulting spectral signal-to-noise. Further, the benefits of our technique combined with continuum subtraction is exemplified when considering non-isolated sources. The source labeled as ‘Deblended Galaxy’ here refers to object ID: 208 from Figure 3.1, it can be seen that the use of the cross-correlation alone induces noise from the contaminating galaxy (as described in Section 3.2.2). However, when employing the additional continuum subtraction step we find a significant increase in the spectral signal-to-noise over all traditional extraction methods. Similar results can be seen for the ‘Deblended Lensing Arc’ which is also shown in Figures 3.2 and 3.5.2.

Again, it is worth mentioning here that any signal-to-noise improvements of the resultant spectrum is highly dependent on the reference used. We find that when the reference is poorly defined, this method is strongly biased by contamination which can result in an overall decrease in signal-to-noise. Similarly, the availability of ancillary imaging data will help define robust reference spectra, and even though in our test cases shown here we find improvements for all objects, for faint sources the white-light image is not always satisfactory to define extractions. A further limitation is the spatial extent of the object; if it is extended such that Doppler shift gradients are non-negligible this technique is not ideal for spectral extractions.

3.3 Software Methods

The python based AUTOSPEC software we introduce here aims to provide the user with a simple, but robust extraction of one-dimensional spectra from IFU

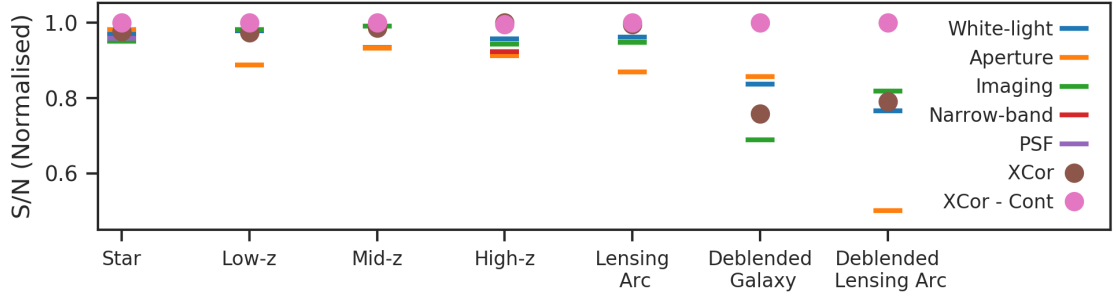


Figure 3.3: We show here the normalised spectral signal-to-noise for a variety of objects and extraction methods. Horizontal lines show traditional weighting schemes: blue and green show spectral extractions weighted by the MUSE white-light image and deep g-band imaging respectively, while orange represents aperture extractions. For the high redshift galaxy we construct a narrow-band image of $100\text{\AA}$ width, centred on the Ly- α emission line, spectral signal-to-noise derived using this image is shown in red. For stellar spectral extractions we employ an additional PSF weighting scheme which we show here in purple. Circular points show the signal-to-noise of spectral extractions weighted via our cross-correlation maps; before (brown) and after (pink) the additional continuum subtraction step. All points shown here represent the median signal-to-noise value across the full wavelength range of the datacube. It can be seen here that in most of the test cases, our cross-correlation methods either improve or are approximately equal to the averaged spectral signal-to-noise of the best traditional extraction method. When it is not, the use of the additional continuum subtraction step helps to improve the resultant signal-to-noise beyond that of traditional methods by an average of $\sim 20\%$. Here, the ‘Deblended Galaxy’ refers to object ID: 208 from Figure 3.1 and the ‘Deblended Lensing Arc’ can also be seen in Figures 3.2 and 3.5.2.

datacubes using both existing techniques along with our novel methods described in Section 3.2. At a minimum, the user is required to supply the software with an IFU datacube along with a catalogue of sources to be extracted. A parameter file is supplied which can be used to fine-tune the functionality of the software to the users requirements. AUTOSPEC makes use of the MUSE Python Data Analysis Framework (MPDAF; Bacon et al., 2016) for various aspects of source extraction and the construction of the output data files.

Initial spectral extractions are performed in which the spatial extent is defined either via user defined apertures, or segmentation regions. Segmentation regions can be automatically calculated within the code or can be supplied by the user (see Section 3.3.1). With one of the initial spectra defined as a reference, the software performs our custom designed cross-correlation algorithm across a truncated datacube centred on the object (see Section 3.3.2). This cross-correlation algorithm provides a detailed insight into which spaxels correspond to the source in question. This analysis is employed as a unique weighting scheme which can be shown to increase the overall signal-to-noise of the resulting spectra. By performing the additional continuum subtraction step, the software can also successfully deblend sources from neighbouring contaminants. In Section 3.3.3 we provide a brief overview of the required input files as well as output products produced.

3.3.1 Initial extraction

For the first step in the extraction procedure AUTOSPEC iterates through each source in the input catalogue and creates a subcube from the supplied IFU datacube. The subcube is centred on the source co-ordinates with its extent defined by the user. The creation of the subcube is a necessary step in improving computational memory usage as well as processing time.

To provide the user with as much flexibility as possible, the AUTOSPEC software

automatically extracts initial object spectra based on individual, or multiple user defined apertures, weight images and segmentation maps. Firstly, aperture spectra are calculated from within circular regions with no additional weighting applied. Secondly, the software will use all user supplied images to derive a segmentation region using Source Extractor, parameter files for which can be supplied by the user if required. It is also possible to perform segmentation region extraction without additional data. However, by supplying ancillary imaging data or segmentation maps, extraction regions can be more accurately estimated. This is especially important for faint sources that are unlikely to be detected directly from the datacubes white-light image. For each additional image supplied, as well as the MUSE white-light image, a weighted spectrum will be calculated using Equation 3.1. Further, if the user has access to existing segmentation maps these can be supplied in place of, or in addition to, those calculated within the software.

3.3.2 Improving spectral quality

To make use of the wealth of information available within the datacube, we provide the user with the option to implement our cross-correlation and continuum subtraction algorithms in order to deblend sources, and perform secondary spectral extractions if required.

If this step is to be undertaken, the user is required to define one of the preliminary spectra (obtained as described in Section 3.3.1) as a reference, this can be done on a source-to-source, or per run basis. The software performs our cross-correlation algorithm across the full subcube using Equation 3.2 and the methods described in Section 3.2.1. The masks used to produce the reference spectrum are also used in this step. This additional masking is not always necessary, but we find in most cases it helps to negate sources of noise and improve flux conservation in these secondary extractions. This analysis yields a weight map,

providing a detailed description of the extent of the source within the datacube itself. This weight map is then used as the basis for a secondary source extraction.

If the subcube is likely to be contaminated by neighbouring objects, the user can also choose to perform the additional continuum subtraction step here. Following the methods described in Section 3.2.2 the target source can be isolated from a neighbouring objects. While subtracting the continuum from the subcube increases the processing time of each source extraction, we find that the resulting spectral quality can be greatly improved (see Figure 3.3). Following this step, AUTOSPEC will produce an additional secondary spectral extraction. In Figure 3.4, we show examples of the spectra extracted for a single object in a run of the AUTOSPEC software. In this case, the software is supplied with a single aperture and an additional image. While it is difficult to see by eye any noticeable improvements in the spectral quality, we note that flux conservation is maintained through all spectral extractions methods undertaken by AUTOSPEC.

3.3.3 Using the software

The software has been designed to be as user friendly as possible. The user is required to supply the IFU datacube along with a catalogue of the central positions (RA and DEC) of sources. The catalogue can be supplied in one of two different formats. If settings are provided on a per run basis, the first three columns of the catalogue are required to be in the format of: Source ID (integer), right ascension (degrees) and declination (degrees). This is compatible with a wide variety of existing catalogues, including those produced by MUSELET which can be input directly to AUTOSPEC. Alternatively, if the user wants to define extraction parameters on a source-by-source basis, they are required to provide two additional columns of data: extraction size of subcube (in arcseconds) and a

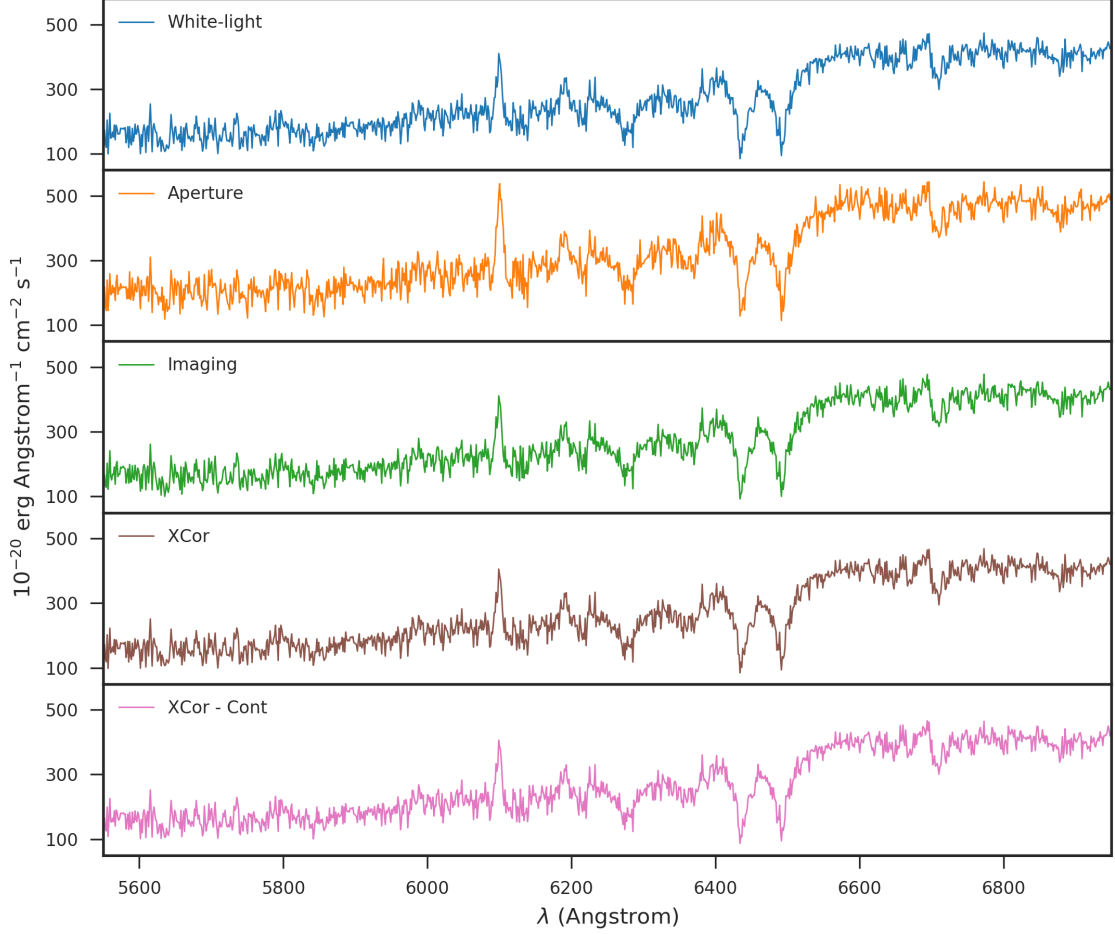


Figure 3.4: Example galaxy spectra extracted via the various methods available within AUTOSPEC. In blue, orange and green we show spectra extracted using traditional methods. Orange shows an extraction defined by a circular aperture while blue and green are masked using segmentation regions generated within the software and weighted by the MUSE white-light, and deep g-band imaging respectively. The g-band weighted spectra is used as a reference in order to define a cross-correlation weight map both before and after continuum subtraction and used to weight spectra shown in brown and pink respectively. For cross-correlation extractions, AUTOSPEC uses the same masks as used by the reference spectrum in order to reduce sources of noise and maintain flux conservation.

reference spectrum label (either aperture or weight image).

The user can supply additional images from which the segmentation region can be defined and weighted extractions will be undertaken. The user can also directly supply SExtractor segmentation maps derived independently of AUTOSPEC. Our software runs through the command line interface via the python environment, and all user settings can be configured via the provided parameter and catalogue files. The AUTOSPEC software and detailed usage instructions are available on GitHub⁴.

We test our software on a standard research computer (Intel i3-6100 3.70GHz CPU with 8GB of ram). After a one time initial set up procedure per run (which will vary depending on the size of the datacube and number of additional images supplied), source extraction typically takes 3-4 seconds per object. This includes 3 aperture extractions, 3 image weighted extractions (including white-light), as well as calculating and extracting cross-correlation weighted spectra before and after the additional continuum subtraction step. Thus, AUTOSPEC is able to effectively process catalogues of hundreds, or thousands of objects in a very short time span.

Output

For each source successfully extracted, the user is presented with a fits format file, the contents of which can be customised according to the users preferences. Additionally, for the ease of the user, AUTOSPEC can output jpg files showing the generated masks, cross-correlation weight maps and spectra obtained for each object.

⁴<https://github.com/a-griffiths/AutoSpec>

3.4 Alternative Uses

The development of the techniques and software as detailed in this Chapter are motivated by work on lensing clusters (Chapter 2) where the identification and extraction of spectra from a MUSE IFU datacube proved to be a laborious process. However, we show here that their application is not limited to a particular type of observation or instrument.

For IFU observations of single galaxies such as those obtained in the Mapping Nearby Galaxies at APO survey (MaNGA; Bundy et al., 2015), our cross-correlation techniques are able to spatially identify small regions with common spectral features. The produced cross-correlation maps may also help to identify the spatial extent of particular galactic components. Additionally, we suggest that a combination of the cross-correlation and continuum extraction techniques as detailed in this Chapter are ideal for the identification of multiple-images to constrain strong lensing models, this however would require significant computing power to be run across large datacubes.

In Figure 3.5, we show the versatility of our cross-correlation method using various datacubes and observations.

3.5 Summary

We find that by utilising the wealth of information available within IFU datacubes, we are able to isolate sources and can obtain increased signal-to-noise spectra. Our cross-correlation algorithm paired with continuum subtraction performs consistently well at deblending sources and providing an unbiased weighting scheme for spectral extractions.

As these techniques are designed for the extraction of a single, one dimensional

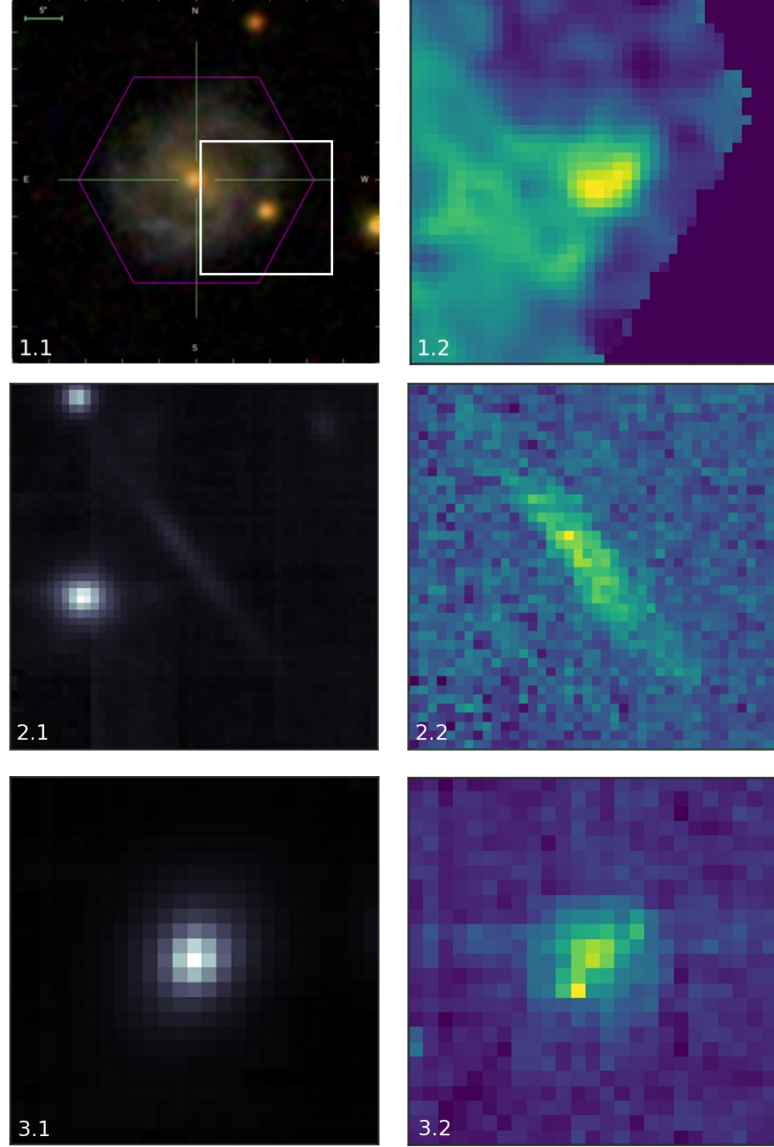


Figure 3.5: Here we show 3 examples demonstrating the power of our source identification methods. Top (1.1) is an SDSS image of a galaxy observed in the MaNGA survey (Bundy et al., 2015), the overlaid white box shows the extraction region and top-right (1.2) shows the cross-correlation map. Middle (2.1 and 2.2) show the MUSE white-light image and cross-correlation strength map of a lensing arc detected in the CLIO cluster (Griffiths et al., 2018). Bottom (3.1 and 3.2), shows a white-light image of a Quasar and the corresponding cross-correlation map from MUSE observations of Quasar Field SDSS J1422-00 (Bouché et al., 2016).

spectrum per object, its usefulness is limited to observations in which sources do not subtend large areas of the sky such that Doppler shift gradients are negligible. Thus, it is best employed for cluster or field studies where these velocity gradients will have minimal effect. As the production of this software was motivated by the work carried out in Chapter 2, we find it is particularly useful for observations of lensing clusters where it is able to successfully identify and extract the spectra of both cluster and background galaxies, as well as extended lensing arcs. However, we have shown that its application is not limited to these types of observations.

We provide a simple-to-use tool for the spectral extraction of small or large catalogues of objects with minimised set-up and run time. While this software has been designed with MUSE observations in mind, it is applicable to any IFU data, provided it can be read by the MPDAF python package. We make this software available under a BSD 3-Clause License via Zenodo (Griffiths, 2018) and GitHub at: <https://github.com/a-griffiths/AutoSpec>.

Chapter 4

Emission line galaxy selection and $H\alpha$ emitters

In this Chapter we combine medium-band observations from the Survey for High- z Absorption Red and Dead Sources (SHARDS) with HST imaging to identify emission line galaxies in two of the Hubble Frontier Field galaxy clusters, Abell 370 and MACS J1149.5+2223. Using detailed flux calibrations, we update photometric redshifts and stellar population parameters. Further, we select for low-mass $H\alpha$ emitters in order to investigate the bursty nature of their star formation histories.

4.1 Introduction

Obtaining an accurate picture of galaxy formation and evolution are amongst the most outstanding questions in astrophysics today. There have been many studies examining these processes in some detail over the past 30 years or so, including extensive Hubble Space Telescope (e.g. Conselice et al., 2003a; Beckwith et al., 2006; Grogin et al., 2011; Duncan et al., 2019) and ground-based imaging studies (e.g. Steidel et al., 2004; Mundy et al., 2017). One of the most critical aspects for studying galaxy formation and evolution is to determine the redshifts of objects such that their evolutionary connections can be made, either through mass or

number density selection to connect systems at different points in their evolution (e.g. Mundy et al., 2015).

Two major ways in which galaxy studies progress is through the investigation of galaxies at different redshifts, and by using the emission of light (direct or indirect) from these systems to measure the amount of current star formation. The process of star formation is fundamental for understanding the assembly of galaxies and how the universe was reionized. However, our resulting understanding of the star formation history of galaxies is largely based on observations of single integrated light measures of SFR within entire galaxies over a variety of redshifts (e.g. Madau & Dickinson, 2014). While much work in this area has been done, we are just starting to understand *how* and *why* star formation is distributed within galaxies. We also know that the sources of reionization are likely galaxies at $z > 6$ (e.g. Duncan & Conselice, 2015), yet we do not know from which types of galaxies, or modes of galaxy formation, ionizing radiation is emitted. Both of these problems can be addressed in unique ways by searching for and characterizing emission line systems in the distant Universe.

There are in general three ways in which galaxies in the distant universe are discovered. The most reliable method is through spectroscopic surveys, in which, by accurately measuring the wavelengths of a few features in the spectrum of a galaxy, its redshift can be determined with a high accuracy (e.g. Zhou et al., 2019). However, spectroscopy of significant samples is still very difficult to obtain and only future programs such as MOONS, WEAVE, PFS and 4MOST will make significant progress towards obtaining large quantities of new redshift information.

Alternatively one can use photometric redshifts to find distant galaxies by fitting intrinsic spectral energy distributions (SEDs) to stellar population models in order to obtain best-fit star formation histories and redshifts (e.g. Dahlen et al., 2013). An alternative simplified version of this is to use the Lyman-break dropout

method, whereby one finds the Lyman-break by searching for galaxies that have a faint, or statistically non-existing flux in an observed filter, traditionally the U-band (e.g. Koo & Kron, 1980; Guhathakurta et al., 1990; Steidel & Hamilton, 1993; Steidel et al., 2004).

The final method is to use line emission as detected in narrow-band imaging. Searching for and examining distant galaxies using line emission through narrow-band imaging has a long history. Traditionally, the Lyman- α line is used to locate and study distant galaxies, (Stark et al., 2010; Ouchi et al., 2010). However, the radiative transfer of Ly- α is very complex (e.g. Gronke et al., 2016) as it is a resonant line, such that its photons scatter with neutral hydrogen, and increase the likelihood of dust absorption due to the short wavelengths. Thus, Ly- α cannot typically be used to trace the SFR in most galaxies unless the escape fraction of Ly- α photons is known (however, the work of Sobral & Matthee, 2019, has calibrated Ly- α SFRs with rest frame equivalent widths to within 0.3 dex). It is much better to use the non-resonant H α (e.g. Geach et al., 2008; Sobral et al., 2013, 2014), or other similar lines such as [O II] or even [O III] (e.g. Khostovan et al., 2015). Likewise, if two lines can be measured from the H II regions (such as O III/O II), their ratios gives an indication for the content of the radiation coming from these star forming areas (e.g. Izotov et al., 2017) and/or dust (however, because of the degenerate nature of line ratios, it is often better to employ other methods for dust corrections).

For line emitters, Ly- α is ideal for finding distant galaxies due to its brightness, but it is difficult to use this line for measuring astrophysical quantities from these galaxies (see Sobral & Matthee, 2019). The emission from H α , [O III] and [O II] lines are, on the other hand, much less affected by dust than Ly- α or UV fluxes. These lines are also good for identifying and measuring galaxies which may have high dust attenuation and thus very faint Ly- α emission. There has been much

progress in this over the past few years. For example, we know that bright $H\alpha$ emitters are very common at low and intermediate redshifts (e.g. Sobral et al., 2012, 2013, 2016). We also have not yet probed the lowest mass galaxies at these epochs. These may also be moderate redshift counter parts to the Lyman-continuum leaking Green Pea galaxies found in the local universe. See for example, Jaskot & Oey (2013) and Yang et al. (2017). They could also be analogues of the systems that reionized the universe (Chapter 5).

Ground-based surveys have used this $H\alpha$ line as a tracer of star formation in distant galaxies (e.g. Sobral et al., 2009, 2012, 2015), finding many sources and a steep luminosity function ($\alpha_{H\alpha} = -1.6$). $H\alpha$ can also be used to investigate the widely variable star formation rates (SFRs) of dwarf galaxies predicted by hydrodynamical simulations (e.g. Smit et al., 2016; Sparre et al., 2017; Emami et al., 2019). Dwarf galaxies are not just simple nearby systems, but are the most common galaxy type in the Universe (e.g. Conselice et al., 2016), but they are extremely difficult to locate and study in the distant Universe. Deep emission line surveys remain one of the best ways to find and study these systems outside the very local Universe, with Ly- α surveys providing some of the lowest mass galaxies (Oteo et al., 2015; Matthee et al., 2016; Santos et al., 2020).

Dwarf galaxies with stellar masses of $M_* < 10^{9.5} M_\odot$ typically experience bursty episodes of star formation on timescales of a few to tens of megayears (Rodighiero et al., 2011; Shen et al., 2014; Sparre et al., 2017; Santos et al., 2020). In order to investigate the bursty star formation of these distant dwarf galaxies, it is necessary to use observables that trace star formation on different time scales. Hydrogen recombination lines such as $H\alpha$ and $H\beta$ are produced by short lived O-stars which have lifetimes of a few megayears such that their emission quickly reaches an equilibrium after the star formation is quenched, allowing us to trace galaxy SFRs on these short timescales. On the other hand, far-ultraviolet (FUV) continuum

photons ($1300\text{\AA} < \lambda < 2000\text{\AA}$) are produced by both O- and B-stars which have much longer lifetimes of ~ 100 Myr such that the FUV emission takes much longer to reach equilibrium. Thus, through the comparison of $\text{H}\alpha$ and FUV it is possible to determine variations in galaxies' star formation rates on timescales of less than 100 Myr (e.g. Glazebrook et al., 1999; Iglesias-Páramo et al., 2004; Lee et al., 2009; Weisz et al., 2012; Domínguez et al., 2015). This is crucial to determine how star formation occurs in these most common galaxies, which are also thought to dominate production of Lyman-continuum photons which reionized the universe (e.g., Duncan & Conselice, 2015, Chapter 5). In this Chapter, we describe a survey for these line emitters, describe their basic properties, and give some information about their star formation histories.

This Chapter is thus organised as follows: In Section 4.2 we discuss the Survey for High- z Absorption Red and Dead Sources (SHARDS; Pérez-González et al., 2013) medium-band observations and data reduction, as well as ancillary data used. Section 4.2.2 details the photometric calibration of SHARDS imaging matched to the deep HST broad-band data. Photometric redshifts and stellar population parameters are calculated in Section 4.2.3. We describe corrections of the broad-band continuum colours and the selection of line emitters in Section 4.3. We present result and investigate the properties of the $\text{H}\alpha$ emission line selected dwarf galaxies in Sections 4.4 and 4.5, and draw conclusions in Section 4.6.

4.2 Observations and data reduction

The following analysis presented in this Chapter is based on new medium-band observations of the Hubble Frontier Fields (HFF) galaxy clusters (Lotz et al., 2017), Abell 370 and MACS J1149.5+2223, and their corresponding parallel fields. We also utilise the datasets and multi-wavelength photometric catalogues made available through the HFF-DeepSpace project (Shipley et al., 2018). We explain the

nature of this data and how we use it in our analyses in the following subsections.

4.2.1 Data Sources

Medium-band observational data

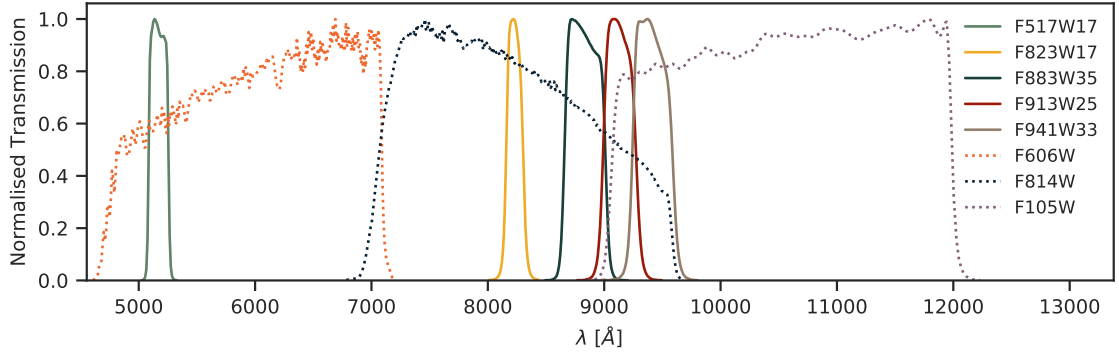
Medium-band (MB) optical imaging data of the Abell 370 and MACS J1149.5+2223 clusters (hereafter A0370 and M1149 respectively), as well as their parallel fields were obtained as part of the SHARDS Frontier Fields survey (SHARDS-FF; PI:Pérez-González). The SHARDS-FF (Pérez-González et al. in prep) survey is an ongoing observation program of two of the Hubble Frontier Fields (HFF) galaxy clusters, obtaining subarcsec-seeing imaging in 25 contiguous filters within the wavelength range 5000-9500 Å, reaching an average spectral resolution $R \sim 50$. Observations are performed using the Optical System for Imaging and low-Intermediate-Resolution Integrated Spectroscopy (OSIRIS) instrument, at the 10.4 m Gran Telescopio de Canarias (GTC) at the Observatorio del Roque de los Muchachos, in La Palma. OSIRIS's 8.5'x 7.8' field of view (FOV) covers both the cluster and parallel HST fields in a single pointing. With observations beginning in December 2015, a total of 240 hours observational time was granted for the program. On completion, the observations will reach at least 3- σ sensitivity of $m \sim 27$ in all the 25 contiguous medium-band filters.

Individual images are reduced using a dedicated OSIRIS pipeline (Pérez-González et al., 2013). The pipeline performs bias subtraction and flat fielding as well as illumination correction, background gradient subtraction and fringing removal. Additionally, the pipeline implements World Coordinate System (WCS) alignment, which includes field distortions, two-dimensional calibration of the passband and zero point and stacking of individual frames.

In order to search for emission line galaxies at a range of redshifts, we use all available SHARDS data; at the onset of this study, observations of A0370 have

Table 4.1: SHARDS Filter details.

Filter	Central Wavelength [Å]	Width [Å]
F517W17	5170	165
F823W17	8230	147
F883W35	8830	336
F913W25	9130	278
F941W33	9410	333

**Figure 4.1:** Transmission curves of the SHARDS and HST filters used for the selection of emission line galaxies. All curves have been individually normalised.

been carried out with four SHARDS filters (F517W17, F823W17, F913W25 and F941W33), while M1149 has been observed in three (F883W35, F913W25 and F941W33). Filter data is provided in Table 4.1 and we show response curves in Figure 4.1. We take this opportunity to note that, at the time of writing, SHARDS-FF observations of A0370 have recently been completed in all 25 contiguous medium-band filters in which raw data is publicly available from day one. Reduced images and catalogues will be published in Pérez-González et al. (in prep.) and are available on direct request.

Ancillary observations and catalogues

For differential flux measurements and the selection of emission line galaxies, we require deep broad-band (BB) multi-wavelength data covering the same wavelengths

as the medium-band filters. For this reason we make use of catalogues and imaging data made available as part of the Hubble Frontier Fields (HFF) Deep Space project (Shipley et al., 2018). These data combine up to 17 ACS/WFC3 filters with ultra-deep Ks band imaging, and Spitzer-IRAC, when available. The HFF-DeepSpace dataset also includes calibrated catalogues, photometric redshifts, lensing magnification factors as well as original imaging data, models and calibration information, providing an ideal ancillary dataset for our candidate selection. We note here that HFF-DeepSpace observations cover only a fraction of the ~ 70 square arcminute area surveyed by SHARDS-FF for each cluster. Considering both the cluster and parallel field, this constitutes roughly $\sim 35\%$ and 38% of the total SHARDS-FF coverage for A0370 and M1149 respectively. In Figure 4.2 we show the HFF-DeepSpace detection image FOV for both clusters and their parallel fields overlaid on SHARDS F913W data.

4.2.2 Photometric calibration

Candidate line emitter selection requires accurate photometric calibration between all observations. This presents a significant challenge when combining ground and space based data due to the differences in spatial resolution, PSFs etc. In order to optimally combine the data, it is necessary to avoid, as much as possible, the degradation of the HST imaging to the lower resolutions of the ground based SHARDS observations, while conversely not artificially up-scaling the low resolution images, likely to provide unreliable flux measurements. To circumvent these issues, we opt to calibrate the medium-band flux measurements following the same procedures used to construct the HST catalogues.

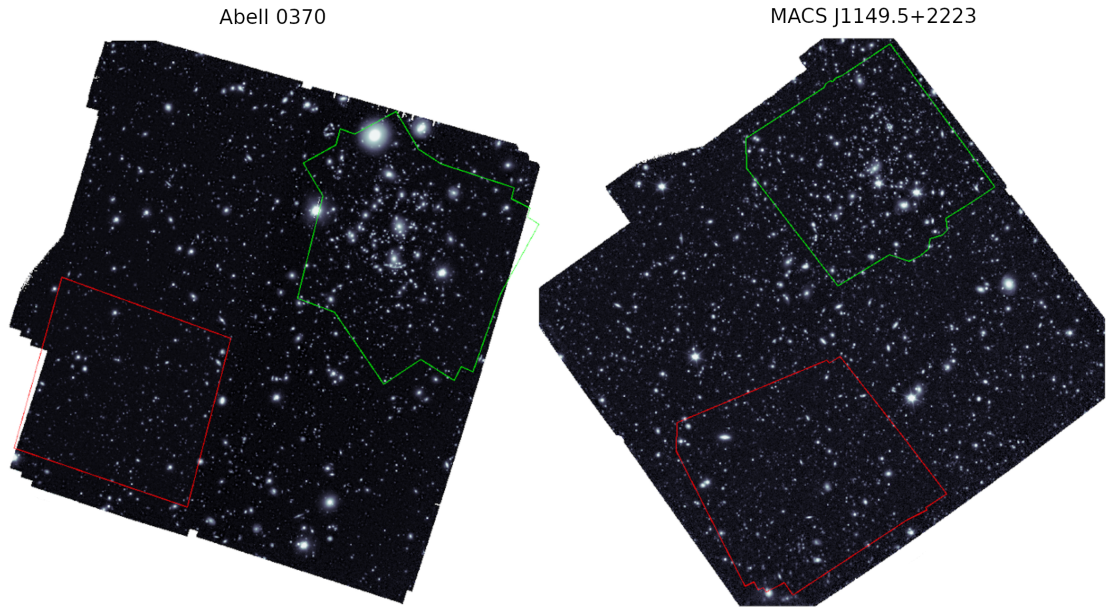


Figure 4.2: Observational field-of-view comparison. SHARDS F913W25 observations of the A0370 (left) and M1149 (right) fields covering roughly $\sim 70'^2$ each. Overlaid in green and red are the composite detection image FOVs for the Hubble space telescope cluster and parallel fields respectively (note that not all of the area within the green and red lines is observed by both WFC3 and ACS). The Hubble data we use comes from from a combination of the F814W, F105W, F125W, F140W and F160W bands, we refer the reader to Shipley et al. (2018) for more information. Essentially, the Hubble field of view is only about 50% of that of the SHARDS imaging field of view.

Total Flux Measurements

All observations are first matched to the PSF of the SHARDS F883W filter ($\sim 1.0''$). This is done by deriving convolution kernels for each band using the PSFs provided as part of both the SHARDS and HFF-DeepSpace datasets. For all HFF-DeepSpace imaging we use $2''$ apertures to recalculate photometry in SExtractor’s dual image mode, utilising the deep detection images from the HFF-DeepSpace data (see Shipley et al., 2018, section 3.3). We perform aperture photometry for SHARDS bands individually, constructing a final catalogue by matching sources detected in the SHARDS filters to the HFF-DeepSpace IDs.

To correct for flux falling outside of the $2''$ apertures, we derive total flux values. Aperture photometry is adjusted by applying a correction factor, derived on a source-by-source basis from a reference band (typically F160W). Firstly, for each galaxy the reference band total flux ($f_{ref,tot}$) is calculated from the SExtractor (Bertin & Arnouts, 1996) AUTO flux using a growth curve, in combination with the Kron radius (for full details see Shipley et al., 2018). A conversion factor is then calculated from the ratio of the reference bands total flux to the corresponding $2''$ aperture flux ($f_{ref}(r)$). Following the equation:

$$f_{i,tot} = f_i(r) \frac{f_{ref,tot}}{f_{ref}(r)} \quad (4.1)$$

where r is the aperture radius, total fluxes for all other bands ($f_{i,tot}$) can be derived based on the measure aperture flux, $f_i(r)$.

It should be noted here that this method of producing our catalogues only provides SHARDS medium-band flux measurements for sources which are also found in the detection HST images (i.e. sources that are emitting in the continuum). While we do find additional sources in the medium-band images not found in the HST which warrant further investigation, it is beyond the scope of this work (but

see Arrabal Haro et al., 2020, for an example using SHARDS data). Below we describe how we apply further flux corrections which are required to robustly combine the medium-band imaging with HFF-DeepSpace data.

Typically, when investigating galaxies within the fields of massive clusters such as those in this study, magnification effects resulting from strong gravitational lensing should be considered. Our $H\alpha$ sample however is situated at, or below the cluster redshifts such that corrections for these lensing effects are unnecessary.

Flux Corrections

In order to obtain consistent measurements between broad- and medium-band photometry, we apply further flux corrections. We correct for Galactic extinction, taking values given by the NASA Extragalactic Database extinction law calculator¹ for the centre of each field and filter (for a full breakdown of extinctions used for HFF-DeepSpace filters, see Table 5 of Shipley et al. (2018)). Further, flux values are normalised to a zero-point of 25.

Geometric effects

Geometric effects due to incidence angles of the GTC/OSIRIS light beam result in spatially varying effective central wavelengths within each filter. This must be corrected for. Sources within each SHARDS observation are detected with similar, but not identical, effective central wavelengths depending on their location within the image. These effects have been calibrated previously in Pérez-González et al. (2013). We also need to include this correction in this work. The variation of the filter's central wavelengths will not only affect the SED and SPS fitting, but also calculations of flux densities, this in turn will induce some shift in the

¹http://ned.ipac.caltech.edu/help/extinction_law_calc.html

calculated equivalent width and excess significance parameters used for the selection of candidate emitters. Thus, accurate calibration of geometric effects need to be undertaken.

Here, we present a summary of this calibration procedure which is described in detail in Pérez-González et al. (2013, Section 3.3). The central wavelength calibration is performed through day-time imaging and laboratory-obtained spectroscopic data. Using a pinhole mask, spectra are obtained covering the entire FOV, from which the transmission curve is measured. The shape and width of the curve remain relatively constant while the central wavelength shows systematic variations around the optical axis (to the left of the FOV). Central wavelengths are fit with a function that depends on the distance from the optical axis squared (r^2). Given the source location and the position of the optical axis, the central wavelength can be computed following the equation:

$$CWL(X, Y) = A + B \times [(X - X_0)^2 + (Y - Y_0)^2] \quad (4.2)$$

where X , Y , X_0 , Y_0 are the pixel locations of the sources, and the optical axis respectively. The values A and B are the fitting coefficients, and, along with the values of X_0 and Y_0 , are filter dependent. The values of these are presented in Table 1 of Pérez-González et al. (2013). Calibrations were tested and found to provide robust central wavelength values over different nights.

4.2.3 Updated Photometric Redshifts and Stellar Population Parameters

We utilise our photometric catalogues combining broad-band data from HFF-DeepSpace with our calibrated medium-band photometry to obtain high quality photometric redshifts and stellar population parameters for all galaxies within both

clusters, and their parallel fields. The photometric fitting codes EAZY (Brammer et al., 2008) and FAST (Kriek et al., 2009) are used for this as default parameter files are provided in the HFF-DeepSpace dataset, allowing for the most robust comparison to existing catalogue values. For a detailed description of parameter selection and verification see Sections 5.2 and 5.4 of Shipley et al. (2018).

Photometric Redshifts

Photometric redshifts are computed with the SED fitting code Eazy² (Brammer et al., 2008). We use a linear combination of 12 galaxy templates based on Flexible Stellar Population Synthesis (FSPS) models (Conroy et al., 2009; Conroy & Gunn, 2010) and trained on the UltraVISTA photometric catalogues (Muzzin et al., 2013). We implement a redshift prior based on F160W apparent magnitudes and use a scaled default template error function.

Due to the variations in the effective central wavelength of the SHARDS filters, EAZY must be run on a source-by-source basis. We employ a custom python code to automate this process and incorporate the object specific filter response curves. In summary; for each object in our catalogue, the code uses a pre-defined set of EAZY parameters in combination with our photometric data to create a set of temporary input files. The SHARDS filter response curves are shifted to the effective central wavelength before EAZY is run on the single object. Once results are obtained for each object, the code then compiles the data into a single catalogue. Spectroscopic redshifts are used when available; otherwise the peak of the photometric redshift distribution (z_{peak}) is taken as the redshift. We compare our updated results with photometric redshifts from the HFF-DeepSpace catalogues in Figure 4.3.

²<https://github.com/gbrammer/eazy-photoz/>

Stellar Population Parameters

Stellar population parameters such as stellar mass, star formation rates and ages are estimated for our sample of emitters with FAST³ (Kriek et al., 2009). For input parameters we again follow the methodology of Shipley et al. (2018); employing a Chabrier IMF (Chabrier, 2003), solar metallicity, minimum age of 10 Myr, Calzetti dust attenuation law (Calzetti et al., 2000), $0 < A_V < 6$ mag and exponentially declining star formation histories with a minimum e-folding time of $\log_{10}(\tau/\text{yr}) = 7$. We use a Bruzual & Charlot SPS model library (Bruzual & Charlot, 2003) which includes random bursts (of duration between $3 \times 10^7 - 3 \times 10^8$ yr) superimposed onto models of continuous star formation histories (SFHs) with a probability that 50% of galaxies have experienced a burst of the past 2 Gyr. We use a solar metallicity here as this is what has been used previously in the HFF-DeepSpace catalogue. Furthermore, the use of solar metallicity only affects the stellar mass measurements, and if our systems are less than solar this would produce stellar masses which differ by 0.3 dex, which is not enough to alter any of our conclusions. FAST models do not currently include emission lines, however their effect on stellar mass estimates has been shown to be small (e.g. Banerji et al., 2013).

In order to obtain the most accurate stellar population parameters, we again shift the SHARDS filter response curves on an object to object basis to account for variations in central wavelength and use our updated photometric redshift estimates (see Section 4.2.3). While the inclusion of the SHARDS medium-band photometry is likely to improve estimates of these parameters, only mass-to-light ratios are well constrained due to their dependence on rest-frame optical colours which are covered by the HFF-DeepSpace photometry. We show in the central, and right panels of Figure 4.3 that our results on measuring these features with our

³<http://w.astro.berkeley.edu/~mariska/FAST.html>

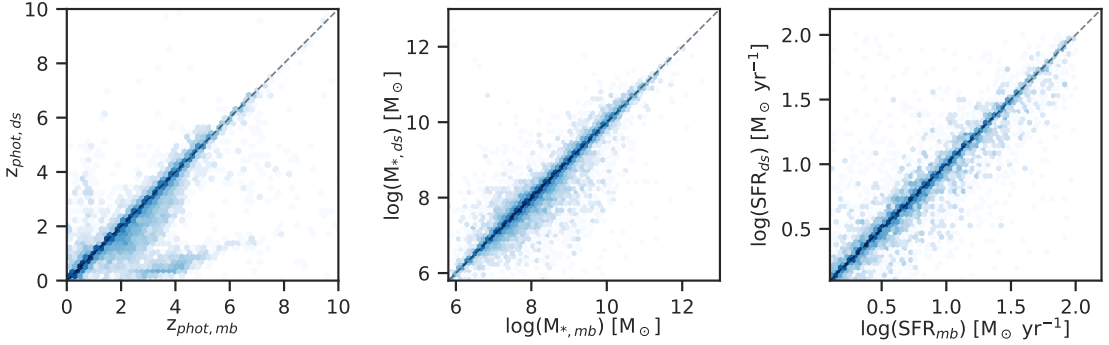


Figure 4.3: Photometric redshift and stellar population parameter comparisons for all objects in both the cluster and their corresponding parallel fields. Left panels shows a direct comparison of photometric redshifts estimated with EAZY from HFF-DeepSpace catalogues and this work (HFF-DeepSpace + SHARDS filters). The grey dotted line represents a one-to-one ratio. Middle and right panels are similar, but for the FAST estimates of stellar mass and star formation rate respectively. In all plots, the subscript ‘mb’ (medium-band) represents estimates obtained in this work, while the subscript ‘ds’ (DeepSpace) denotes the values obtained from the HFF-DeepSpace catalogues.

broad band and narrow band imaging are in good agreement with HFF-DeepSpace parameters.

4.3 Emission Line Galaxy Selection

In order to select emission line objects via differential flux measurements, we require overlapping wavelength coverage of both the medium- and broad-band imaging. We utilise F606W and F105W broad-band imaging to match the F517W and F941W medium-band filters respectively, while F814W is matched to both the F823W and F913W bands. We note here that the area covered by the F105W band is less than half the size of that covered by F814W imaging (only $\sim 42\%$ and $\sim 34\%$ the size of the F814W science area for the cluster and parallel fields respectively). For the robust selection of emission line objects, we employ a two-parameter selection criterion, as is well established in previous studies (e.g. Sobral et al., 2009; Matthee et al., 2015; Santos et al., 2016; Sobral et al., 2017; Arrabal Haro et al., 2020). This criterion assures that the objects selected show a real colour excess, and not

an excess due to random scatter or measurement uncertainties.

4.3.1 Broad-band Continuum

Before applying the two-parameter selection criterion, it is important to note that the medium-band filter profiles are not centrally aligned with the corresponding broad-band filters. Thus, sources with significant intrinsic colour in the continuum can complicate not only the selection of emission line objects, but also result in over or underestimation of line fluxes. In order to correct for this, we derive an effective broad-band magnitude (called BB') to account for the slope in the continuum and achieve a mean zero (BB-MB) colour (Sobral et al., 2012, 2013, 2018). To obtain the most accurate estimates, we first remove all point sources from the catalogue using the *star_flag* identifier. A further cut is then performed to select sources within 2σ of the scatter around the median of the broad-band colour. We then perform a linear fit which is used to correct the initial broad-band magnitude following the form:

$$(BB' - MB) = (BB - MB) - M(RB - BB) + C \quad (4.3)$$

where *RB* is the reference band (taken as the closest neighbouring broad-band filter), and *M* and *C* are the coefficients of the linear fit. For sources in which one of the broad-band colours is not available, the median correction is applied. We show (BB-MB) colours before and after corrections have been applied in Figure 4.4.

4.3.2 Selection

To carry out a selection for our emission line candidates, first we make a check to determine if the medium-band excess is high enough to be considered an emission line object. This is done by setting a lower limit on equivalent width (EW). The

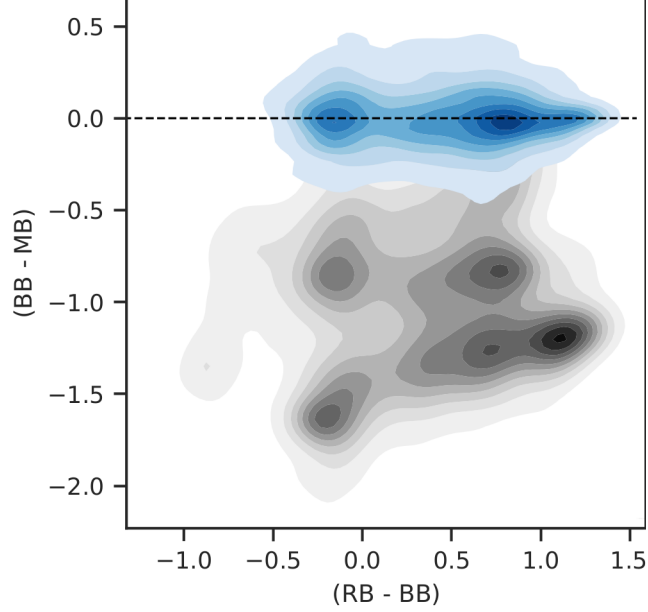


Figure 4.4: Colour-colour plot showing broad-band continuum magnitude corrections for all objects in both Frontier Field clusters and their corresponding parallel fields. We show object colours before (grey contours) and after (blue contours) corrections have been applied to achieve a mean-zero BB-MB colour.

equivalent width is the ratio between the flux of an emission line (medium-band) and the flux density of the continuum (broad-band). We follow the basic procedure used in previous searches and specify a traditional excess criterion of rest-frame EW of $25\text{\AA}$ (e.g. Ouchi et al., 2008). Previous studies (Ouchi et al., 2010) have found that higher EW cuts help to minimise contamination from low redshift interlopers, while Sobral et al. (2017) are able to implement much lower cuts through the use of narrower filters. Due to the limited sample size and low expected EW at our modest redshifts we use the lower limit of $25\text{\AA}$ (e.g. Ly et al., 2007; Villar et al., 2008). To obtain an EW from the observed medium-band excess, magnitudes (m_i) are converted to flux densities (f_i) for each filter (i) via the equation:

$$f_i \text{ (erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}\text{)} = \frac{c}{\lambda_{i,\text{centre}}^2} 10^{-0.4(m_i+48.6)}, \quad (4.4)$$

where c is the speed of light and $\lambda_{i,\text{centre}}(\text{\AA})$ is the filters central wavelength (note

that for the medium-band filters, this is taken as the corresponding broad-band central wavelength as the continuum colour corrections of Equation 4.3 have been applied). Line fluxes and equivalent widths are then computed using:

$$f_{line} \text{ (erg s}^{-1} \text{ cm}^{-2}\text{)} = \Delta\lambda_{MB} \frac{f_{MB} - f_{BB}}{1 - \frac{\Delta\lambda_{MB}}{\Delta\lambda_{BB}}} \quad (4.5)$$

and

$$EW \text{ (\AA)} = \Delta\lambda_{MB} \frac{f_{MB} - f_{BB}}{f_{BB} - f_{MB} \frac{\Delta\lambda_{MB}}{\Delta\lambda_{BB}}} \quad (4.6)$$

respectively, where $\Delta\lambda_{MB}$ and $\Delta\lambda_{BB}$ are the widths (in $\text{\AA}$) of the medium- and broad-band filters respectively. Here, f_{MB} and f_{BB} are the flux densities calculated via Eq. 4.4. Depending on the specific filters used, this equation breaks down at certain MB excess when $\Delta\lambda_{MB}/\Delta\lambda_{BB} \rightarrow f_{BB}/f_{MB}$ such that the denominator tends to 0. When this occurs we set the EW of the sources to $> 1500\text{\AA}$ as this can also be helpful to identify sources that may not be real, or where problems may have arisen.

The second parameter, the excess significance (Σ , e.g. Bunker et al., 1995) is used to quantify the real flux excess compared to an excess due to random scatter. The excess significance can be written as (Sobral et al., 2013):

$$\Sigma = \frac{1 - 10^{-0.4(BB-MB)}}{10^{-0.4(ZP-MB)} \sqrt{\pi r_{ap}^2 (\sigma_{px, BB}^2 - \sigma_{px, MB}^2)}} \quad (4.7)$$

where MB and BB are the broad- and medium-band magnitudes respectively (see also Sobral et al., 2018, for aperture based methods). Here, ZP represents the normalised zero point (25) and r_{ap} is the aperture radius in pixels. The root-mean-square (rms) of the background pixel values, σ_{px} , are estimated by randomly placing empty apertures across the respective images. A selection criterion of $\Sigma > 3$ is used to classify sources as potential line emitters (Sobral et al., 2013).

We show the selection of potential line emitters in Figure 4.5. From $\sim 25,000$ objects across the four fields (two clusters and their respective parallels), 666 candidates are found in the cluster fields with a further 432 in the parallels, providing a total of 1,098 candidate line emitters. Through the use of our photometric redshift estimates with the detection filter throughput information, it is possible to assign suspected emissions lines to objects within our sample. For example; we find 42 $H\alpha$ candidates as well as 33 $O II$, 63 $O III + H\beta$ and 3 suspected $Ly\alpha$ line emitters. We also find 42 candidate emission line galaxies between redshifts $2 < z < 3.5$ which will be used to investigate escape fractions in Chapter 5. In Figure 4.6 we show the updated photometric redshifts for our candidate emission line galaxies as a function of HFF-DeepSpace photo- z (i.e. without SHARDS medium-band filters) and updated stellar mass (see Section 4.2.3), highlighting a few example emission lines only.

4.3.3 $H\alpha$ Emitters

We select low-mass $H\alpha$ emitters, which are the focus of the rest of this Chapter, from our emission line sample based on a combination of the detected filters and updated photometric redshifts. We utilise filter throughput information for all medium- and broad-band filter combinations to determine the redshift range in which the detected emission line coincides with $H\alpha$. When a galaxy is selected as an emission line candidate via the two parameter selection criterion (as described in Section 4.3) and its photometric redshift coincides with the $H\alpha$ emission line for the detection filter combination (with tolerances of $\Delta z \sim 0.2$ determined by filter widths), the object is marked as a $H\alpha$ emitter. We find a total of 42 objects meeting this criterion over the four fields, and summarise the redshift range for all filter combinations in Table 4.2.

Given the luminosity functions of Sobral et al. (2013) at $z = 0.4$, we would

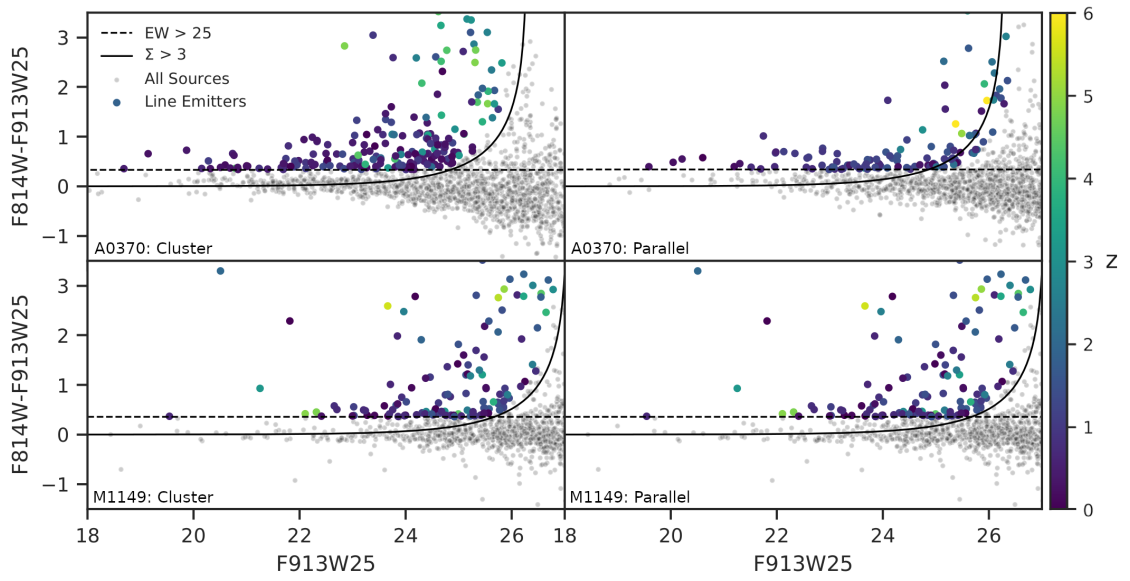


Figure 4.5: Medium-band excess as a function of F913W medium-band magnitude for the A0370 and M1149 clusters (top left and bottom left panels respectively) and their parallel fields (top right and bottom right panels). The horizontal dashed lines represents a rest-frame EW cut of $25\text{\AA}$ while solid lines show the average 3.0Σ colour significance. All objects are shown as grey points while galaxies that meet the selection criteria are coloured by photometric redshift. Sources with spectroscopic redshifts are shown as coloured stars.

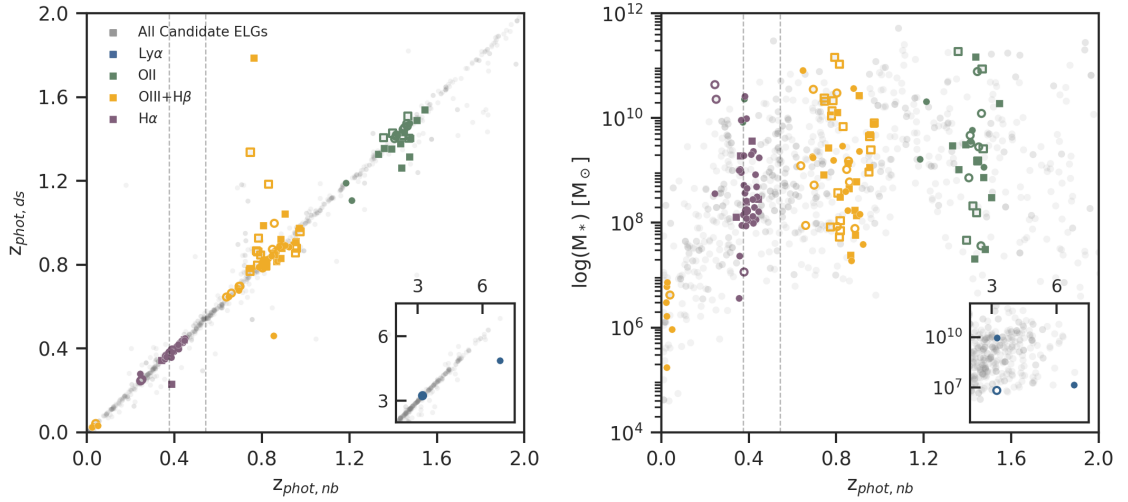


Figure 4.6: Left panel: redshift comparison of emission line selected candidates with ($z_{phot,mb}$), and without ($z_{phot,ds}$) SHARDS medium-band filters. We show a few example emission lines based on the detected medium-band filter and photometric redshift, other emission line candidates are shown as grey points. Candidates selected from the A0370 and M1149 fields are shown as circles and squares respectively, while filled and empty points represent the cluster and parallel fields. The redshift of the clusters are shown by dashed vertical lines at 0.375 (A0370) and 0.543 (M1149). The inset shows the same again from $2 < z < 7.5$, illustrating the detection of 3 Lyman- α emitters. Right panel: Stellar mass as a function of photometric redshift for all candidate objects. Coloured points correspond to the same emission line selected candidates as left panel.

expect to find roughly 4 H α emitters within our fields. This is consistent with our results if the overdensity in the A0370 cluster field can be attributed to the sources being cluster members. This is further supported by the work of Stroe et al. (2017) in which 9 narrow band filters are used to select over 3000 H α emitters from 19 galaxy clusters and their large scale environments (beyond 2 Mpc from cluster centre). Their results indicate that cluster fields are overdense in H α emitters, with the luminosity function showing a strong dependence on the dynamic state of the cluster. Considering recent simulations suggesting A0370 is a merging system (Molnar et al., 2020) along with the volume probed by the SHARDS data, our results are consistent with the work of Stroe et al. (2017) finding similar number densities of H α emitters.

We visually inspect all objects which are within a crowded environment or contain contaminating flux from neighbouring sources. In total we find 4 candidates which cannot be successfully isolated. These objects are excluded from our analysis as the overlapping light profiles have the potential to result in unreliable photometry, as well as systematic shifts in our morphological and structural measurements.

33 of the remaining 38 candidate galaxies are selected from the A0370 field; this is expected as the redshift of the A0370 cluster ($z = 0.38$) corresponds to that of our detection range such that we are able to select both foreground galaxies and cluster members. We show the distribution of our H α candidates within the A0370 cluster field in Figure 4.7. However, as M1149 is at the slightly higher redshift of $z = 0.54$ we are unable to probe the cluster population with our available filter combinations.

We note here that this process is undertaken for all chosen emission lines, but a full analysis of all these emitters is beyond the scope of this work.

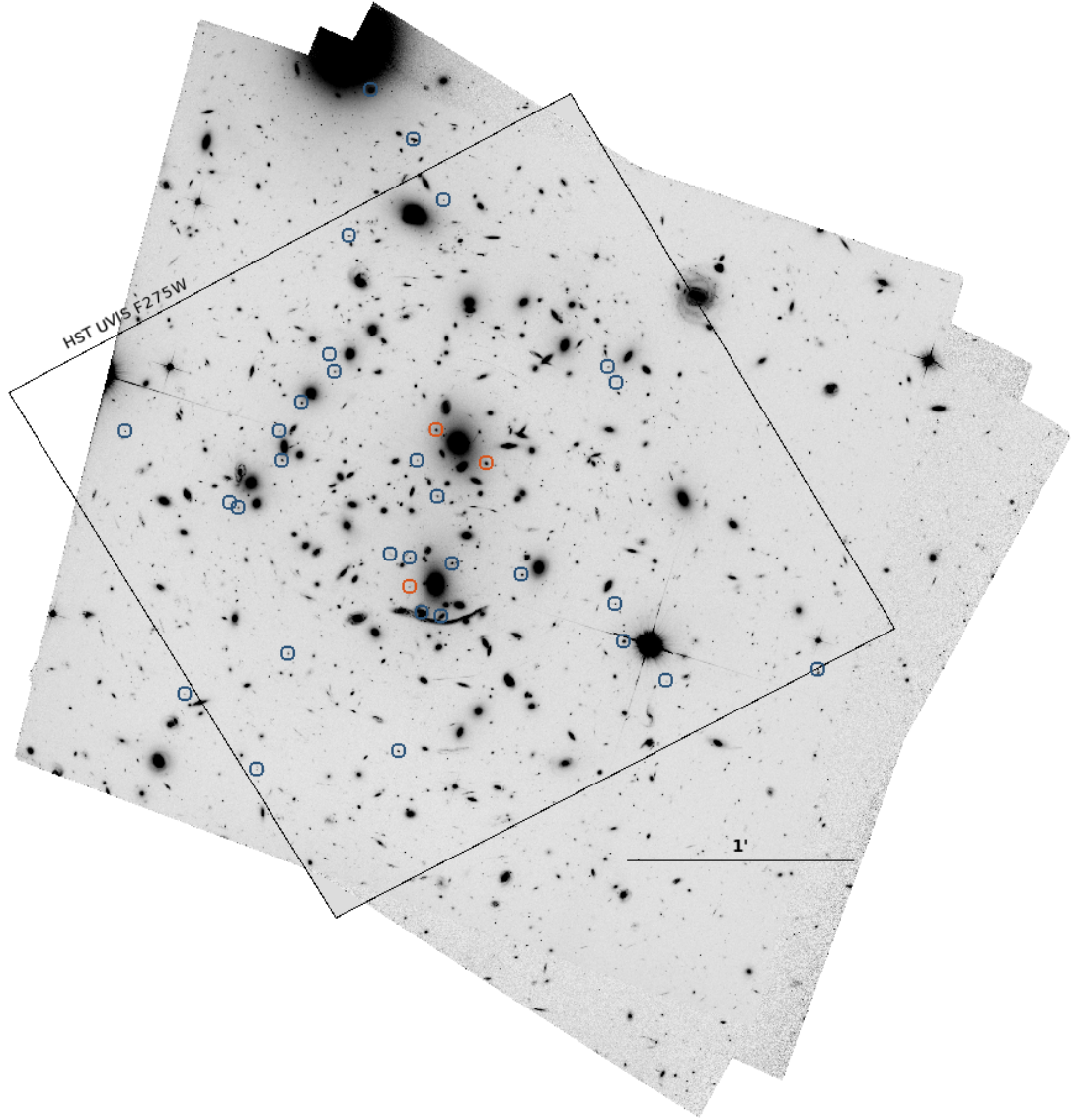


Figure 4.7: Hubble Space Telescope F814W image of the A0370 cluster field with locations of candidate $H\alpha$ emission line sources denoted by open blue circles. Orange circles mark the location of objects found to be undergoing a recent burst of star formation following the analysis in Section 4.4.4. The HST/UVIS F275W FOV is displayed by the black contour.

Table 4.2: Detection filter redshift range and cluster candidate counts of H α emitters.

MB	BB	Redshift Range	# M1149	# A0370
F517W	F606W	-	-	-
F823W	F814W	$0.24 < z < 0.27$	-	3
F883W	F814W	$0.32 < z < 0.37$	2	-
F913W	F814W	$0.37 < z < 0.41$	1	19
F941W	F105W	$0.41 < z < 0.46$	2	11

Removal of [NII] line contamination

Calculations of H α emission line fluxes and equivalent widths must take into consideration the contributions of neighbouring [N II] lines at $\lambda_{rest} = 6548$ and $6583\text{\AA}$. As these lines are situated in close proximity to H α , their flux is typically included in photometric measurements, acting to artificially increase line fluxes and EWs measured. To account for this, we implement a correction based on the work of Villar et al. (2008) where it was found that the fractional contribution of the [N II] flux decreases with increasing EW due to lower metallicities. The flux ratio, $F_{\text{NII}}/F_{\text{H}\alpha}$ and equivalent width, $\text{EW}(\text{H}\alpha + [\text{N II}])$ are related by:

$$\log(F_{\text{NII}}/F_{\text{H}\alpha}) = -5.78 + 7.63x - 3.37x^2 + 0.42x^3 \quad (4.8)$$

where x is $\log(\text{EW}(\text{H}\alpha + [\text{N II}]))$. We use this relation to correct all H α fluxes in this study whereby we find a median correction of $\sim 25\%$.

Extinction correction

The H α emission line is much less affected by dust obscuration than other common lines such as Lyman- α or [O II], but dust effects are non-negligible and should be accounted for, particularly when deriving star formation rates (Garn et al., 2010; Ibar et al., 2013). When spectroscopy is available for individual sources,

the amount of extinction can be estimated by comparing the intrinsic Balmer decrement with that observed. As spectroscopy of each individual sources is often unfeasible, dust extinctions can also be estimated via the comparison of $H\alpha$ and far-infrared SFRs (Ibar et al., 2013; Koyama et al., 2013).

Some studies employ a simple approach of applying a constant value of dust extinction throughout. As determined by Kennicutt (1992) a 1 mag extinction of $H\alpha$ can be adopted and is often a good approximation for the true extinction (e.g. Ly et al., 2007; Geach et al., 2008; Sobral et al., 2009) although it has been found to be stellar mass dependent in the local universe (Garn & Best, 2010), in clusters (Sobral et al., 2016), and at high redshift (Sobral et al., 2012). However, as SEDs are readily available for our galaxy candidates, we estimate dust attenuation based on stellar $E(B-V)$ values derived during fitting (see Section 4.2.3) and the assumption of $A_{v,stars} = 0.44A_{v,gas}$ found in local starburst galaxies (Calzetti et al., 2000). We find all galaxies have a dust content such that $0 < E(B-V) < 0.7$ with mean, median and dispersion of 0.16, 0.06, and 0.20 respectively. This shows that these galaxies are not very dusty systems.

Star formation rates

A galaxy's star formation activity changes throughout its lifetime due to various physical processes such as major/minor mergers and supernovae feedback. These fluctuations can be observed through the luminosity of the $H\alpha$ emission line, which is sensitive to instantaneous star formation on timescales of the order ~ 10 Myr (e.g. Kennicutt, 1998). Thus, the burstiness of star formation activity can be investigated through the direct comparison of $H\alpha$ derived SFRs with those estimated via UV continuum emission, which provides time averaged SFRs over a much longer (~ 100 Myr) period (e.g. Kennicutt, 1998).

As the UV continuum traces star formation over a wider range of stellar ages

than that of $H\alpha$, our calibrations must trace a galaxies SFR history for at least the last 100 Myr. As such, we derive UV star formation rates from rest-frame 1600Å emission (F_{uv}) for our $H\alpha$ sample. The UV flux corresponds to the F275W band (which is provided in the HFF-DeepSpace dataset for both clusters) and corrected for reddening using the stellar $E(B-V)$ values derived from SED fitting, before being converted to luminosity (L_{uv}) following the equation:

$$L_{uv}(\text{erg s}^{-1} \text{ Hz}^{-1}) = 4\pi D_L^2(z) F_{uv}(\text{erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}) , \quad (4.9)$$

where $D_L^2(z)$ is the luminosity distance at the redshift of the source. SFRs are obtained from the Kennicutt (1998) relation adapted from a Salpeter, to Chabrier (2003) IMF following Muzzin et al. (2010):

$$\text{SFR}(\text{M}_{\odot}\text{yr}^{-1}) = 0.8 \times 10^{-28} L_{UV}(\text{erg s}^{-1} \text{ Hz}^{-1}) . \quad (4.10)$$

To provide a consistent set of calibrations, we convert corrected $H\alpha$ fluxes ($F_{H\alpha}$) into luminosities ($L_{H\alpha}$) before calculating star formation rates using the standard calibration of Kennicutt (1998), again modified to a Chabrier (2003) IMF following Muzzin et al. (2010):

$$L_{H\alpha}(\text{erg s}^{-1}) = 4\pi D_L^2(z) F_{H\alpha}(\text{erg s}^{-1} \text{ cm}^{-2}) , \quad (4.11)$$

$$\text{SFR}(\text{M}_{\odot}\text{yr}^{-1}) = 4.5 \times 10^{-42} L_{H\alpha}(\text{erg s}^{-1}) , \quad (4.12)$$

assuming Case B recombination at $T_e = 10^4\text{K}$ and continuous star formation. All measurements are based on line luminosities in which the $[\text{N II}]$ contamination has been accounted for and dust attenuation is assumed to follow $A_{v,stars} = 0.44A_{v,gas}$,

as discussed in Section 4.3.3. While this calibration assumes continuous star formation on timescales of over 100 Myr, it is relatively robust to variations in recent star formation history (if it has been fairly continuous when averaged over periods of tens of Myr, for more discussion see Kennicutt (1998)).

We use these star formation rates to investigate the possibility of bursty star formation histories of these dwarf galaxies at moderate redshifts. We note that estimations based on Equations 4.10 and 4.12 assume a constant SFR for more than 100 Myr. However, for a robust comparison of $H\alpha$ and UV SFRs in this analysis, the absolute SFR scale is less important than a consistent set of calibrations. As $H\alpha$ and UV luminosities depend on the shape of the upper IMF for a given age, we expect the $H\alpha$ to UV ratio to vary no more than 30% for typical IMF slopes (e.g. Glazebrook et al., 1999).

4.3.4 Structure and Morphologies

We have used the Morfometryka (Ferrari et al., 2015) application version 8.2 to measure the structure, non-parametric morphology and Sersic profiles of the sources investigated here. We briefly describe Morfometryka below; please refer to Ferrari et al. (2015) for full details.

Morfometryka takes as input the galaxy stamp image and the related PSF, then segments it and measures basic geometric parameters (e.g. centre, axis length, position angle). Next, it quantifies radial light distribution $I(R)$ from which the Petrosian Radius R_p (Petrosian, 1976) and the half-light radius is estimated. For subsequent measurements, a Petrosian Region with the same geometric parameters as the galaxy and with a radius of $1.5 R_p$ is used. We also use it to measure classic non-parametric morphology indicators, like the CAS system (Conselice et al., 2003b; Conselice, 2014). Additionally, it fits a 1D Sersic profile (Sersic, 1968) for the quantified $I(R)$ and uses the derived parameters as initial guesses to fit a

2D Sersic profile directly to the image of the central source. The structural and morphological measurements used in Section 4.4.5 are summarised in Table 4.3, including error estimated for the Asymmetry and Concentration measurements and χ^2 for the Sersic profile fitting.

4.4 Results

4.4.1 Emission line candidates

Using the methods outlined in Section 4.3, we select emission line candidates based on differential flux measurements using medium- and broad-band data. SHARDS fluxes are calibrated to match broad-band HST measurements, and corrected for filter geometric effects (Equation 4.2) and broad-band continuum colour (Figure 4.4). We then implement a two parameter selection criterion in order to minimise contamination from low redshift interlopers and the effects of random scatter. This selection process yields a total of 1,098 candidate emission line galaxies from both clusters and their parallel fields (see Figure 4.5).

We identify emission lines by updating photometric redshift estimates through integrating all available SHARDS medium-band data. Using the SED fitting code EAZY (Brammer et al., 2008) on a source-by-source basis, SHARDS filter response curves are shifted to the effective central wavelength of each object, allowing for robust photometric redshift estimates (see Figure 4.3). In a similar manner, we update HFF-DeepSpace stellar population parameters using the FAST (Kriek et al., 2009) code.

Our updated photometric redshift estimates allow for the identification of the emission lines responsible for the observed flux excess, as shown in Figure 4.6. Our sample is dominated by [O II] and [O III]+H β emitters (Ly et al., 2007; Khostovan et al., 2015). We find 3 Lyman alpha candidates within our fields at a number

Table 4.3: Summary of the structure and morphology measurements of selected sample

ID	z	M _*	n	χ^2	C	C _{error}	A	A _{error}	R ₅₀ [kpc]	Label
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
443	0.39	8.23	1.16	3.11	3.16	0.07	0.08	3.77e-05	1.23	No UV
466	0.25	10.36	8.24	42.52	2.96	0.02	0.08	3.96e-06	0.30	No UV
492	0.38	7.06	0.97	436.74	2.69	0.30	0.05	1.01e-03	0.57	No UV
1060	0.36	7.37	1.57	3.07	2.91	0.15	0.07	2.18e-04	0.81	Non-Bursty
1095	0.44	8.45	0.99	33.72	2.46	0.08	0.10	2.27e-04	1.00	Non-Bursty
1247	0.37	8.16	1.18	11.13	2.56	0.07	0.15	5.93e-05	1.10	Non-Bursty
1612	0.39	8.24	1.03	1.69	3.05	0.13	0.07	1.54e-04	1.16	No UV
1706	0.40	8.05	0.87	9.72	2.50	0.15	0.05	2.20e-04	1.00	No UV
1796	0.38	8.72	4.95	47.84	2.55	0.06	0.12	3.31e-05	0.38	No UV
2002	0.39	8.09	0.80	11.34	2.51	0.08	0.25	6.79e-05	1.53	Non-Bursty
2092	0.42	9.37	0.82	2.79	1.72	0.03	0.11	7.46e-04	1.95	No UV
2346	0.38	8.57	2.05	2.65	2.98	0.10	0.16	9.55e-05	1.01	Non-Bursty
2485	0.44	8.50	1.16	46.77	2.50	0.11	0.03	1.98e-04	0.83	Bursty
2699	0.37	8.96	1.54	12.39	2.96	0.06	0.03	4.12e-05	0.81	Non-Bursty
2921	0.36	9.03	2.11	4.03	3.48	0.06	0.13	4.23e-05	1.00	Non-Bursty
2936	0.44	8.69	1.34	5.39	2.69	0.10	0.05	1.23e-04	1.06	Non-Bursty
3265	0.25	10.64	6.09	43.57	2.67	0.01	0.08	3.07e-06	0.33	No UV
3328	0.43	8.07	1.17	13.32	2.59	0.15	0.06	2.82e-04	0.98	Non-Bursty
3367	0.39	8.66	1.58	4.38	3.25	0.08	0.19	8.93e-05	1.68	Non-Bursty
3486	0.43	8.92	1.36	6.38	2.85	0.08	0.11	6.07e-05	1.41	Non-Bursty
3728	0.39	8.42	0.99	23.38	2.57	0.12	0.03	1.63e-04	0.83	No UV
3764	0.43	8.30	0.93	2.94	2.74	0.07	0.12	5.59e-05	1.11	Non-Bursty
3900	0.45	9.25	1.37	2.52	3.24	0.04	0.03	2.38e-05	1.38	Bursty
4033	0.42	8.13	1.35	1.69	2.70	0.12	0.06	1.68e-04	0.94	Non-Bursty
4080	0.41	9.56	1.78	5.86	2.92	0.03	0.12	1.95e-05	4.31	Bursty
4371	0.41	9.31	1.34	13.81	2.74	0.05	0.02	3.81e-05	0.86	Bursty
4435	0.38	9.29	1.04	15.97	3.29	0.06	0.06	6.27e-05	0.73	No UV
4476	0.42	7.99	0.88	3.12	2.44	0.16	0.03	3.31e-04	1.20	Non-Bursty
4652	0.42	8.45	0.96	1.25	2.62	0.10	0.03	1.09e-04	1.13	No UV
4661	0.24	8.56	1.79	4.10	3.45	0.07	0.29	4.98e-05	0.99	Non-Bursty
4702	0.36	6.56	0.65	4.49	2.43	0.15	0.30	3.67e-04	0.86	Non-Bursty
4742	0.39	8.40	0.47	20.89	2.57	0.16	0.32	5.83e-04	1.10	Non-Bursty
5504	0.34	8.11	1.55	6.22	3.29	0.06	0.36	9.01e-05	1.31	Non-Bursty
5615	0.39	7.94	0.89	21.57	3.51	0.10	0.17	1.05e-04	1.26	Non-Bursty
5867	0.39	8.25	1.64	35.13	2.67	0.15	0.13	1.99e-04	0.78	No UV
6061	0.36	9.28	1.62	93.03	2.60	0.07	0.08	1.11e-04	0.61	Non-Bursty
6212	0.36	9.00	1.13	4.80	3.15	0.03	0.11	1.51e-05	1.66	No UV
6497	0.36	9.96	1.51	2.87	3.28	0.03	0.07	1.41e-05	1.40	No UV

Table columns: (1) ID; (2) Photometric redshift; (3) Stellar mass in $\log(M_*/M_\odot)$; (4) Sersic index for a 2D profile; (5) $\tilde{\chi}^2$ of the Sersic profile fitting; (6) Concentration; (7) Error in Concentration; (8) Asymmetry; (9) Error in Asymmetry; (10) Half-Light Radius; (11) Label

density that is consistent with current luminosity functions (e.g. Konno et al., 2018; Guo et al., 2020). Of these sources, two are at $z \sim 3$, while the other is a previously unknown $z \sim 7$ object. As mentioned, this Chapter focused on the dwarf $H\alpha$ emitters as they are the closest systems to us and therefore are affected less by dust and redshift. They are therefore easier to study, and give us some idea for how line emitters in the relatively nearby universe behave.

4.4.2 $H\alpha$ main-sequence

First, we investigate the star formation rates of our low-mass $H\alpha$ emitters and how these correlate with other properties. A crucial tool for understanding galaxy evolution is the star forming main sequence, or SFR-stellar mass relation. We present in Figure 4.8, $H\alpha$ derived SFRs as a function of stellar mass. $H\alpha$ SFRs are calculated using the Kennicutt (1998) conversion factor following corrections as detailed in Section 4.3.3, while stellar masses are measured using the SPS fitting code, FAST (Kriek et al., 2009). The green line shows the $z = 0.4$ (redshift of our sample) main sequence parameterization of Speagle et al. (2014), derived from rest-frame UV continuum based star formation rates.

In Figure 4.8 we also show the $SFR_{H\alpha}$ - M_* relation for the $z = 0.4$ $H\alpha$ emitter sample selected from the narrow-band High-Z Emission Line Survey (HiZELS; Sobral et al., 2013) in blue, and from the study of the rich cluster Cl 0939+4713 (Koyama et al., 2013) in orange.

As can be seen, we find a strong $SFR_{H\alpha}$ enhancement of more than a factor of 2 for almost all galaxies in our sample over the Speagle et al. (2014) parameterization. This is indicative of a recent star burst in a galaxy's history; the excess in $SFR_{H\alpha}$ is further enhanced at low masses if one is to consider the Whitaker et al. (2014) parameterization, which finds a steep low-mass slope and has been shown to be consistent with not only UV and IR star formation indicators, but also that of $H\alpha$.

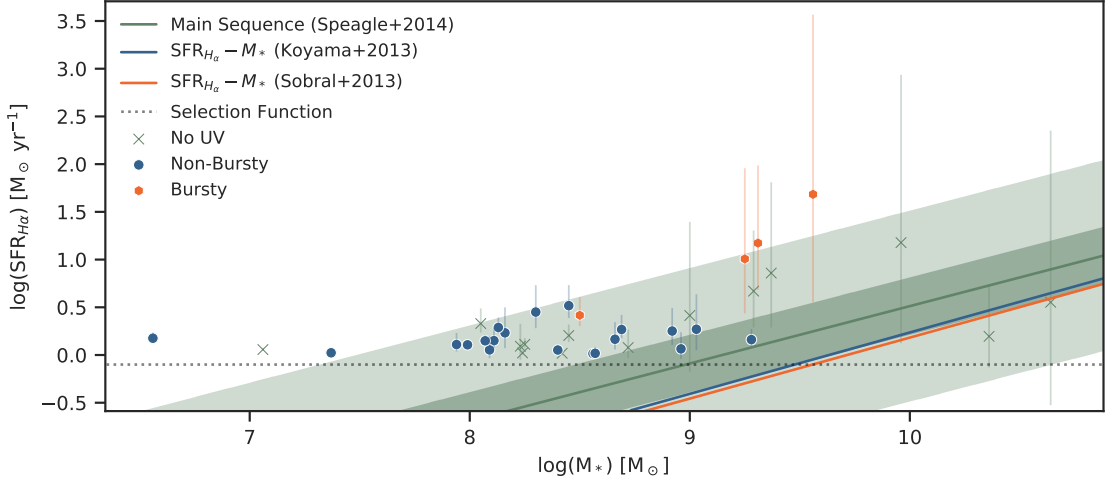


Figure 4.8: Main-sequence of $z \sim 0.4$ line emitters with $H\alpha$ derived star formation rates. Black dotted line shows the selection function while the green line shows the main-sequence parameterization from Speagle et al. (2014) at $z = 0.4$. Dark, and light coloured bands have a width of a factor of 2 and 10 respectively. $SFR_{H\alpha}$ - M_* relations of $H\alpha$ selected galaxies (at $z = 0.4$) from HiZELS (Sobral et al., 2013) and a rich cluster study (Koyama et al., 2013) are shown as orange and blue solid lines respectively. Errors are extrapolated from uncertainties in luminosity and as such should be taken as lower bounds on the full error.

We also find significant enhancement over the $SFR_{H\alpha}$ - M_* relations of both Sobral et al. (2013) and Koyama et al. (2013) for most of our galaxies. This suggests that the observed excess in $SFR_{H\alpha}$ is due to a real enhancement of recent star formation activity, as opposed to a effect of our selection procedure. We later compare the $H\alpha$ star formation rates to the UV measured star formation rate to find galaxies which exhibit ‘bursty’ star formation histories.

4.4.3 $H\alpha$ equivalent width vs stellar mass

In order to assess our selection of $H\alpha$ emission line candidates and their utility in the investigation of bursty star formation in these distant dwarfs, we show the relation between $H\alpha$ rest-frame EW and specific star formation rate (sSFR) in Figure 4.9. $H\alpha$ equivalent widths are calculated via Equation 4.6 and converted to rest-frame values using our updated photometric redshift estimates. Specific star

formation rates are estimated from line fluxes corrected for dust extinction and line contamination before utilising the Kennicutt (1998) conversion factors and stellar mass estimates from the SPS modelling. Local galaxy measurements from the Sloan Digital Sky Survey (York et al., 2000) are shown in grey for comparison. The data are obtained using the web-based DR12 (Alam et al., 2015) query tool⁴ and taken from the *Galspec* products in the value added MPA-JHU spectroscopic catalogue (Brinchmann et al., 2004).

We show in Figure 4.9 that we are able to successfully select galaxy candidates over a range of equivalent widths that exhibit high specific SFRs when compared to typical local galaxies. This can be attributed to the predominantly low masses of the sample, as well as a possible enhancement of $H\alpha$ flux due to recent bursts of star formation.

To gain further insight into our sample and the possibility of bursty star formation histories, we include the evolutionary track of an example galaxy modelled with Starburst99⁵ (Leitherer et al., 1999). We show the evolutionary track (yellow line) of an individual stellar population model of initial mass $10^6 M_{\odot}$, undergoing a single burst of star formation, while model ages of 1 Myr, 5 Myr and 10 Myr are represented by the yellow points.

4.4.4 Bursty star formation

From the previous sections it is clear that we have discovered a highly starforming population of moderate to low-mass galaxies at moderate redshifts. The nature of these objects is however a mystery and in the next sections we determine the properties of these systems, including their possible bursting nature, as well as

⁴<http://skyserver.sdss.org/dr12/en/tools/search/sql.aspx>

⁵<http://www.stsci.edu/science/starburst99/>

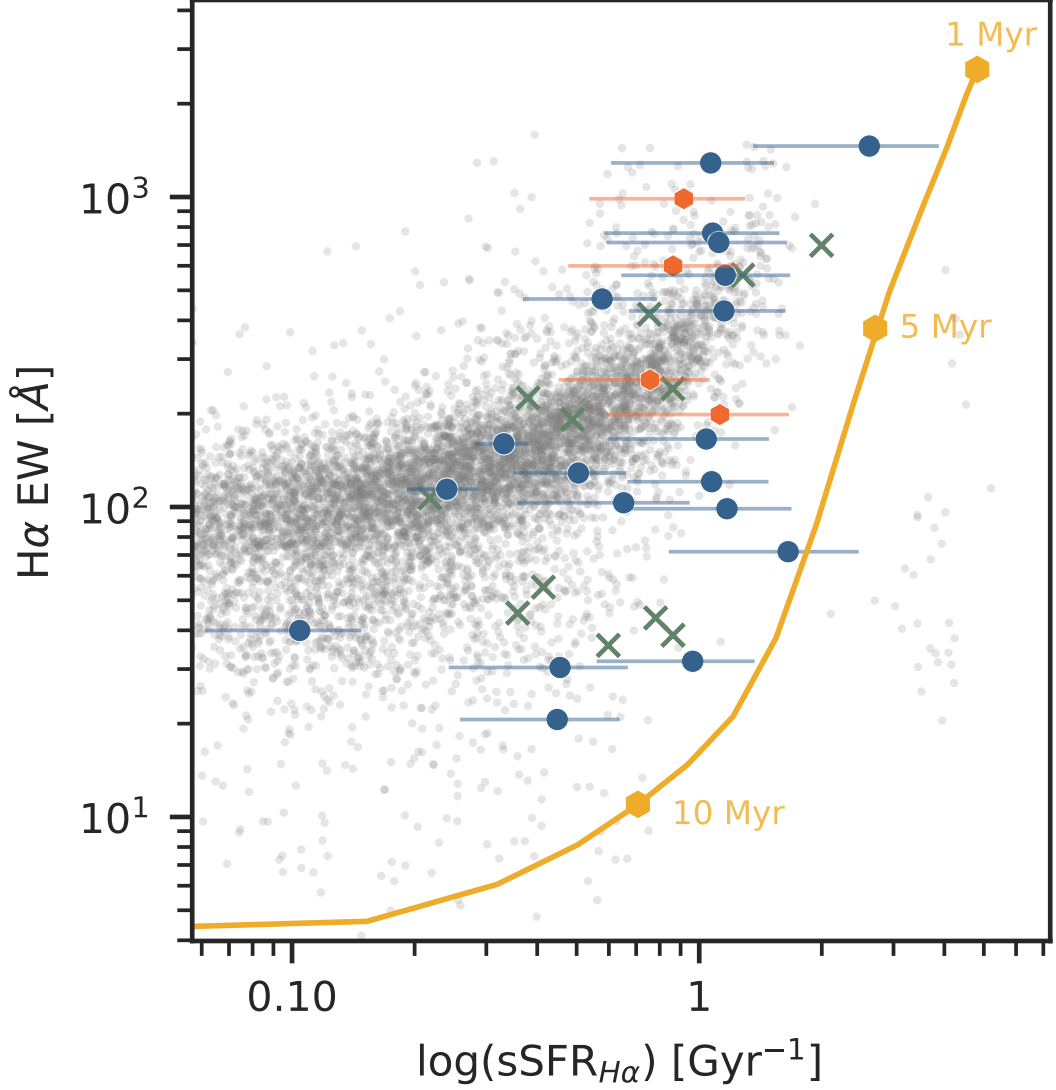


Figure 4.9: Relation between $H\alpha$ rest-frame EW and sSFR. Equivalent widths are calculated via Equation 4.6 and stellar masses are obtained through SED fitting as detailed in Section 4.2.3. Candidates from this study are marked by blue points and compared to local SDSS galaxies (Brinchmann et al., 2004) shown as grey dots. We include a stellar population model from Starburst99 (Leitherer et al., 1999) for reference. The yellow track shows the evolution of a single burst of star formation of a single stellar population and an initial mass of $10^6 M_{\odot}$, ages of 1 Myr and 5 Myr shown as yellow points.

their structure, environment and other properties.

Comparison of $H\alpha$ and UV derived SFRs

In this section we compare the derived star formation rates for our sample by comparing the $H\alpha$, to FUV fluxes. Ideally these two star formation rates should be the same if they measure the same aspects of star formation. However, for galaxies in which the recent star formation rate is more episodic or bursting, we will find that the measured $H\alpha$ SFR will be higher than that measured from UV. The reason for this is that during a star formation episode, the star formation rate measured with $H\alpha$ will be higher during the initial burst than the UV measured star formation as detailed in Section 4.1. After some time, the $H\alpha$ measured star formation will become more similar to the UV measured one.

In Figure 4.10 we present a comparison of SFRs derived from $H\alpha$ and UV luminosities in order to provide a direct visualisation of bursty star formation activity. $H\alpha$ line fluxes are initially computed via Equation 4.5 to account for a non-zero continuum before we apply corrections for dust extinction and [N II] line contamination. UV luminosities are derived directly from reddening corrected rest-frame 1600Å emission, corresponding to the F275W band at $z \sim 0.4$. In order to obtain SFRs from $H\alpha$ and UV corrected luminosities, we use the method described in Section 4.3.3. We also include the evolutionary tracks of two example galaxies modelled with Starburst99 (Leitherer et al., 1999). In yellow, we show the track from Figure 4.9, representing a single burst of star formation of initial mass $10^6 M_{\odot}$, while in green we show the evolutionary track of a model stellar population with a constant rate of star formation of $1 M_{\odot} \text{ yr}^{-1}$ (green line) and indicate the SFR at ages of 1 Myr, 10 Myr and 100 Myr by the green points.

For galaxies with a constant star formation history, $H\alpha$ derived SFRs usually match closely to values derived from the UV. In Figure 4.10, we show the one-to-

one ratio of $H\alpha$ and UV SFRs, representing the equilibrium value of a constant star formation rate. The 0.3 dex margin accounts for variations around the main sequence due to changes in star formation activity, such as mergers, gas flows or active galactic nuclei (AGN) feedback. We find only 4 galaxies display significant enhancement of over 0.3 dex, indicative of a recent burst in star formation activity. We note that a number of systems exhibit $SFR_{H\alpha}/SFR_{UV}$ ratios of less than one, which can be attributed to a galaxy being in the post-burst phase, or consisting of a relatively young stellar population formed through a single burst of star formation. We discuss this further in Section 4.4.4 below.

There are however some important caveats in the direct comparison of SFRs. Firstly, the conversion from luminosities to SFRs induce uncertainties due to unknown factors, such as the initial mass function (IMF), stellar populations, metallicities (Boselli et al., 2009) and the choice of $A_{H\alpha}$ to A_{UV} relation. Uncertainties in the IMF arise as a result of galaxies with a less abundant population of high-mass stars to ionize hydrogen, these objects will have similarly low ratios of $H\alpha$ -to-FUV as those undergoing bursty star formation (Lee et al., 2009). For low-mass galaxies, these effects becomes particularly important, and luminosity-to-SFR conversions are expected to differ from the standard Kennicutt (1998) prescriptions (Ly et al., 2016). Further sources of uncertainty arises from the dust parameterization (Kewley et al., 2002) and $[N II]/H\alpha$ flux ratios. However, low-mass galaxies such as those in our sample are less affected by dust, while luminosity to SFR conversions and variations in $[N II]/H\alpha$ line ratios are not sufficient to account for the excess in $H\alpha$ derived SFRs of our sample.

Specific star formation rates

The relatively high $SFR_{H\alpha}/SFR_{UV}$ ratios present in our sample can be attributed to bursts of star formation, in which $H\alpha$ flux from short-lived O-stars is boosted

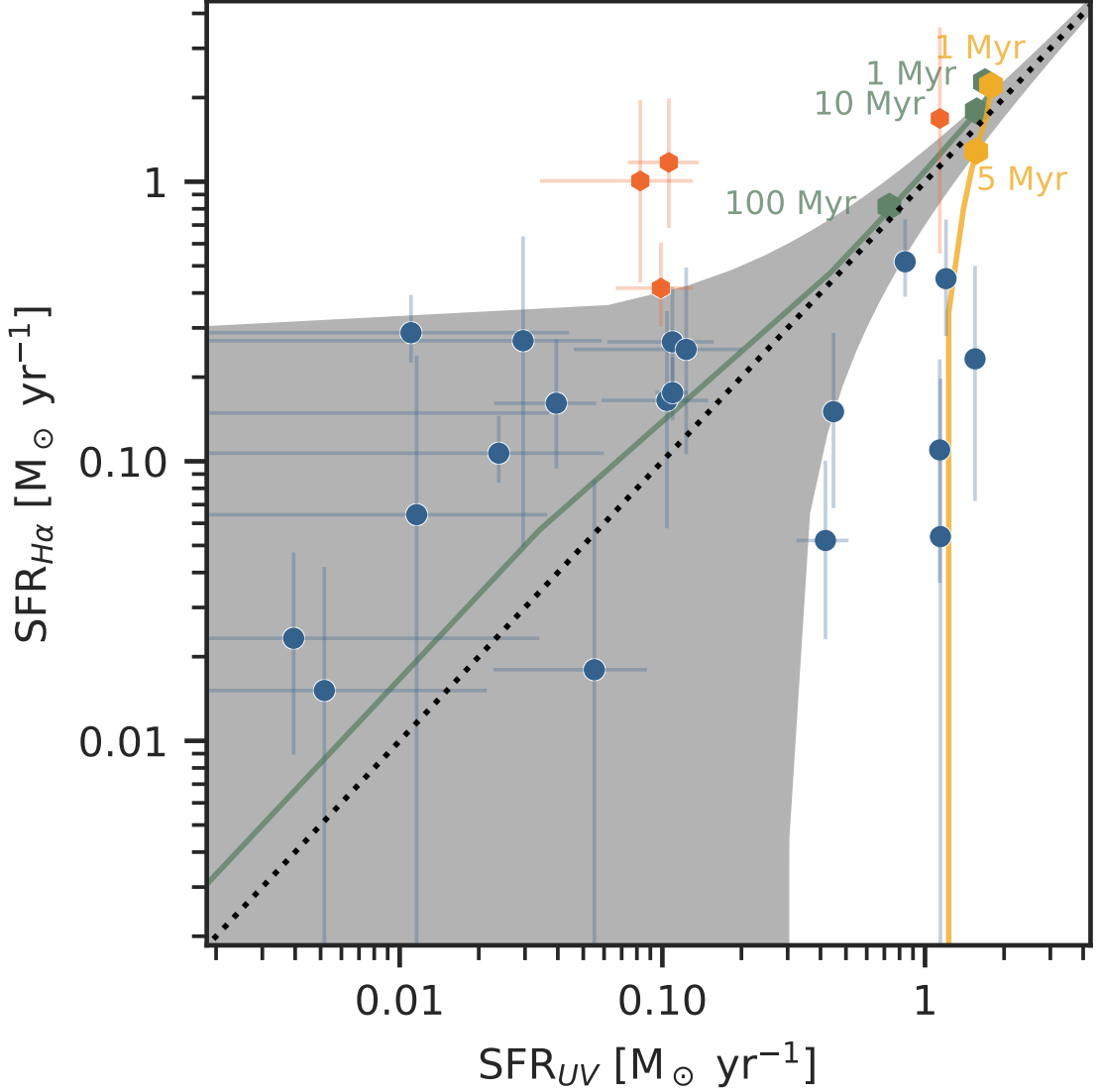


Figure 4.10: Comparison of the $H\alpha$ and UV SFRs. $H\alpha$ line fluxes are corrected for dust extinction and $[N II]$ line contamination while UV luminosities are dust corrected using stellar $E(B-V)$ values derived from SED fitting. Black dotted line shows a one-to-one ratio with a 0.3 dex margin, accounting for typical scatter in star formation activity due to mergers, gas flows or AGN feedback. We include two stellar population models from Starburst99 (Leitherer et al., 1999) for reference. The green track shows a model stellar population with a constant star formation history of $1 M_{\odot} \text{ yr}^{-1}$, with ages of 1 Myr, 10 Myr and 100 Myr marked by green points. While the yellow track shows a single burst of star formation of a single stellar population and an initial mass of $10^6 M_{\odot}$ and ages of 1 Myr and 5 Myr shown as yellow points.

with respect to that of the UV. However, it can also be explained by the assumption of predominantly young galaxies formed in a single burst of star formation. As can be seen in (Figure 4.10), models with a bursting star formation are able to match these values better than a constant star formation rate, except for the bursts which have a higher $H\alpha$ based star formation rate.

In order to further investigate the origin of the observed enhancement in $SFR_{H\alpha}$, we present the $H\alpha$ specific star formation rate (sSFR) as a function of UV sSFR in Figure 4.11. The sSFR is defined as the measured star formation rate divided by the stellar mass. It gives some idea of the whether the star formation ongoing when a galaxy is observed is an important component of its mass formation. Again showing the evolutionary tracks of two Starburst99 models as discussed in Figures 4.10 and 4.9, and Sections 4.4.3 and 4.4.4.

As shown by the evolutionary tracks in Figure 4.11, the specific SFRs of a galaxy undergoing constant star formation (green line) eventually settles into equilibrium with little deviation. This is however not the case for a young galaxy formed under a single burst of star formation (yellow track), in which an enhancement in $H\alpha$ is expected for the first ~ 5 -10 Myr, but rapidly decreases with age as star formation is shut off. Thus, for a recent burst of star formation we would expect galaxies to be above the one-to-one relation of $sSFR_{H\alpha}$ to $sSFR_{UV}$. After some time these sources with ages >10 Myr after the burst would drop below this high excess. For our sample as a whole, we find no reason to favour young galaxy ages over bursty star formation histories as deviations from the one-to-one relation are typically within the margins expected due to perturbations such as gas flows or mergers. We note that $\sim 15\%$ of our sources exhibit a deficit in $sSFR_{UV}$ over that of $H\alpha$ which could be attributed to young ages, but is more likely due to those galaxies being in the post-burst phase.

As can be seen in Figure 4.11, our bursty sample, as defined by having a

significantly larger SFR in $H\alpha$ than in the UV, are not well fit by either the constant star formation or the single burst. This is likely due to the fact that the bursts we see are occurring on top of the existing mass. From Figure 4.11, we can see that the difference is about a factor of ~ 30 , showing that the ongoing burst is about $\sim 3\%$ of the galaxies mass, which would be consistent with an older system which is undergoing a new burst of star formation.

4.4.5 Structure and Sizes

Using the methodology explained in Section 4.3.4, we measure the structures and sizes of our galaxies to understand about their origin in more detail. From the previous sections we know that these $H\alpha$ systems are undergoing star formation, with a small number undergoing bursts. The sizes and structures of these systems may illuminate how these systems are having their star formation triggered.

In Figure 4.12 we show the distribution of the sizes vs. mass for our sample. As can be seen, we clearly are finding systems that are significantly more compact than the size-mass relation for nearby galaxies (from Lange et al., 2015) would predict. We also compare our objects to size-mass relations derived from $z = 0.4$ star-forming galaxies selected on $H\alpha$ emission. Stott et al. (2013) and Paulino-Afonso et al. (2017) both acquire samples of (> 400) $H\alpha$ emitters from HiZELS (Sobral et al., 2013) designed to provide a well-defined statistical sample of star-forming galaxies across the peak of star formation rate density. From these size-mass relations (dotted and dashdot lines in Figure 4.12) it can be seen that (with the exception of ID:4080) our galaxies are clearly much more compact than typical $H\alpha$ emitters of corresponding mass and redshifts.

In terms of other aspects of the structure, we find that there is a range of Sersic index values for our systems, but that most of them are around $n=1$, suggesting that these systems are more disk-like rather than spheroidal, consistent with previous

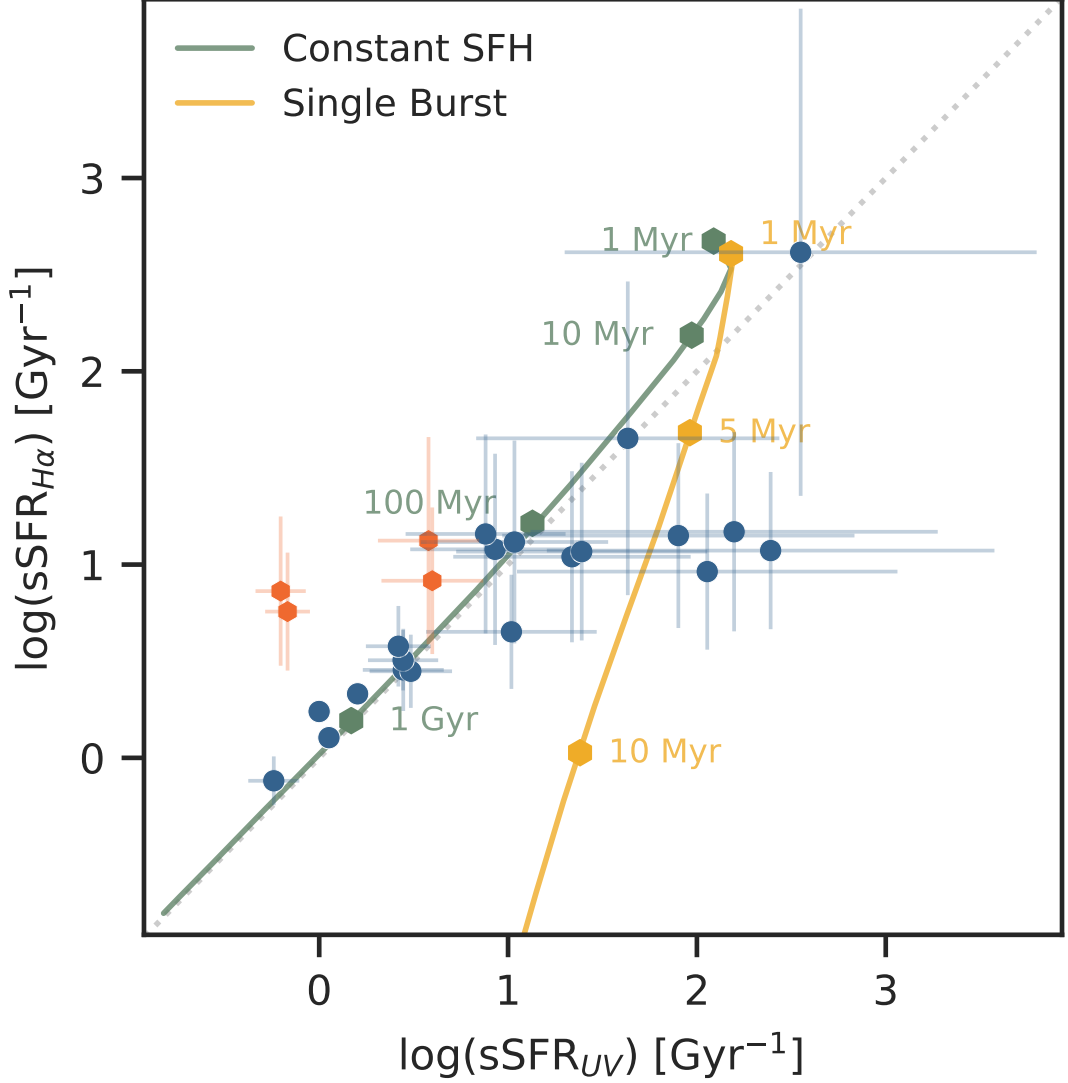


Figure 4.11: Specific star formation rates derived from $H\alpha$ and UV luminosities. $H\alpha$ line fluxes are corrected for dust extinction and $[N\text{ II}]$ line contamination while UV luminosities are dust corrected using stellar $E(B-V)$ values derived from SED fitting. Stellar masses used in the calculation of the sSFR are also obtained through SPS modelling (see Section 4.2.3). We include two stellar population models from Starburst99 (Leitherer et al., 1999) for reference. The green track shows a model stellar population with a constant star formation history of $1 M_{\odot} \text{ yr}^{-1}$, with ages of 1 Myr, 10 Myr, 100 Myr and 1 Gyr marked by green points. While the yellow track shows a single burst of star formation of a single stellar population and an initial mass of $10^6 M_{\odot}$ and ages of 1 Myr, 5 Myr and 10 Myr shown as yellow points.

investigations of $H\alpha$ emission line galaxies (e.g. Paulino-Afonso et al., 2017). This can also be gleaned by investigating the visual morphologies of these systems shown in Figure 4.13 where most of them appear to be disk-like objects rather than ellipticals.

Furthermore, the bursting galaxies do not show any signs of being mergers. They are not found in the merger space of the C-A diagram (Figure 4.14) and do not appear to have a merger morphology when examined by eye (see Figure 4.15). This implies that these systems are not having their star formation triggered by merging activity. This is a strong sign that other mechanisms, besides merging, are responsible for producing the star formation within these systems.

4.5 Discussion

This Chapter presents our analysis of line emitters found within two frontier fields, Abell 370 and MACS J1149.5+2223. We present our analysis of finding these emitters and give a basic overview of the systems we find, including high- z Lyman- α emitters. As a first attempt at studying these systems, we present an initial analysis of the $H\alpha$ emitters which we have discovered at $z = 0.4$ within these two fields. The rest of the Chapter is an analysis of these $H\alpha$ emitters, and how they can provide information about the way in which low-mass dwarf galaxies are undergoing star formation at late times in the universe.

We find a significant number of these low-mass star forming galaxies typical for cluster environments (e.g. Stroe et al., 2017). The enhancement in $SFR_{H\alpha}$ is likely due in part, to our procedure for finding such systems, as we are more likely to find higher star formation given the requirement that a significant amount of detection is found within our medium-band imaging. However, comparisons with $SFR_{H\alpha}$ - M_* relations derived from $z = 0.4$ $H\alpha$ emission line galaxies (Sobral et al.,

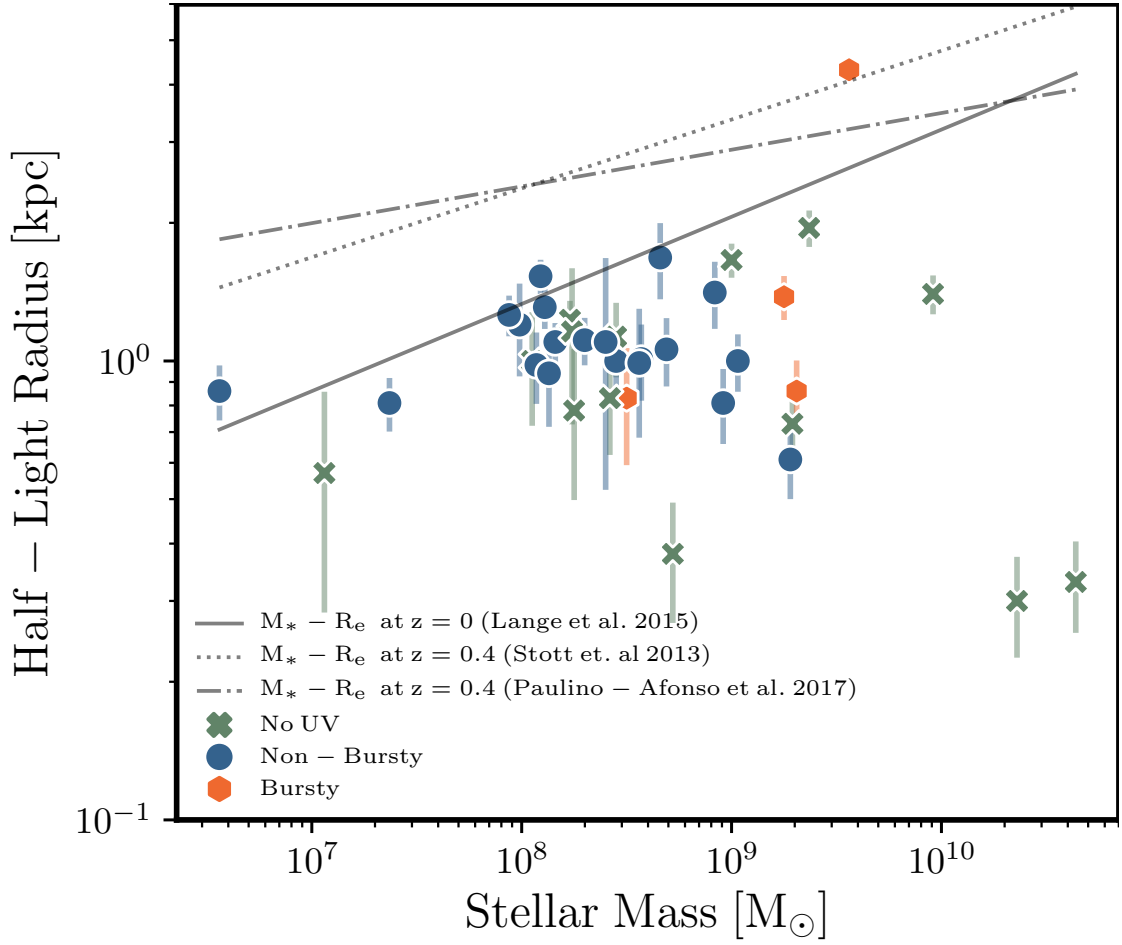


Figure 4.12: The size mass relation for our sample of galaxies. Points are coloured according to the different ways our sample has been selected and measured. Solid, dotted and dashdot lines show the size mass relations from Lange et al. (2015), Stott et al. (2013) and Paulino-Afonso et al. (2017) respectively.

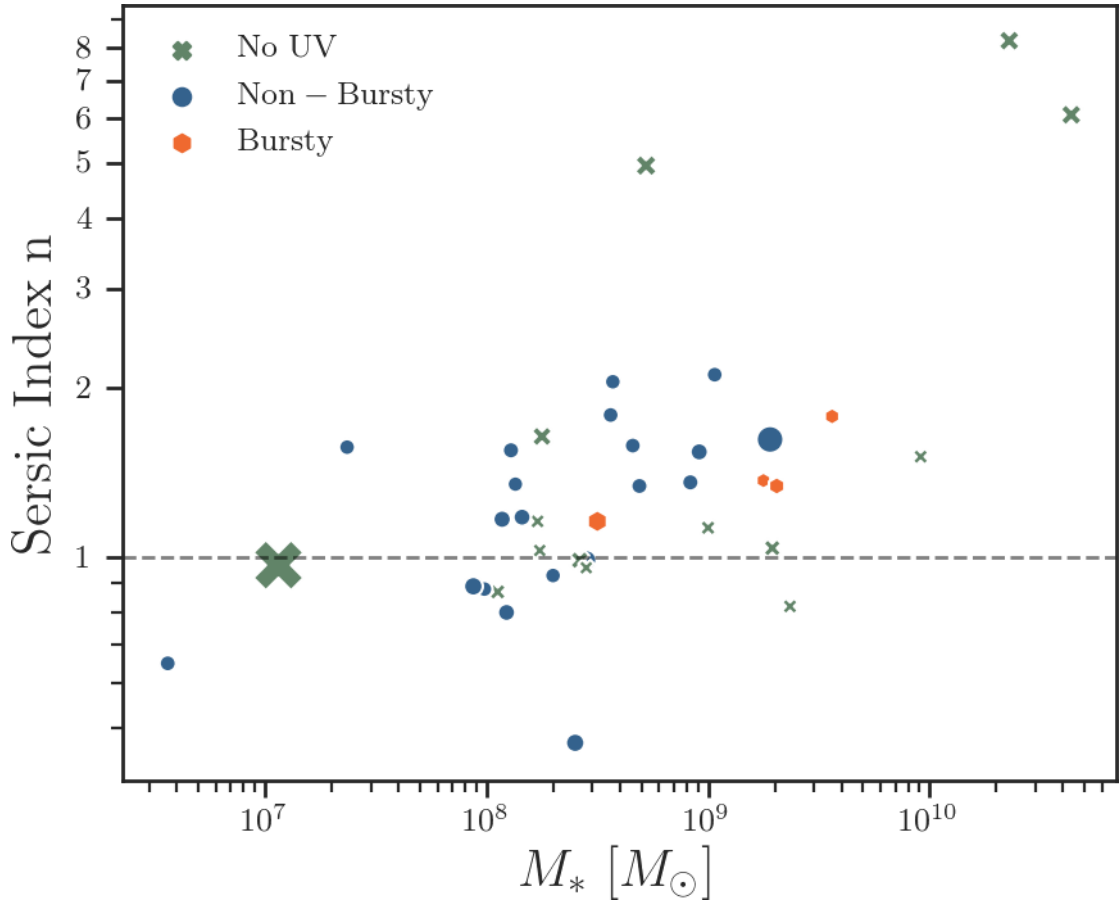


Figure 4.13: The relation between Sersic index, n and the stellar mass. Here we see the differences between our sample’s structure with mass, showing that many of the bursty systems are found at the high mass end of our relation as well as have Sersic indices suggestive of disk galaxies. Size of the points is proportional to the $\tilde{\chi}^2$ of the Sersic profile fitting, bigger points represent more uncertain fits.

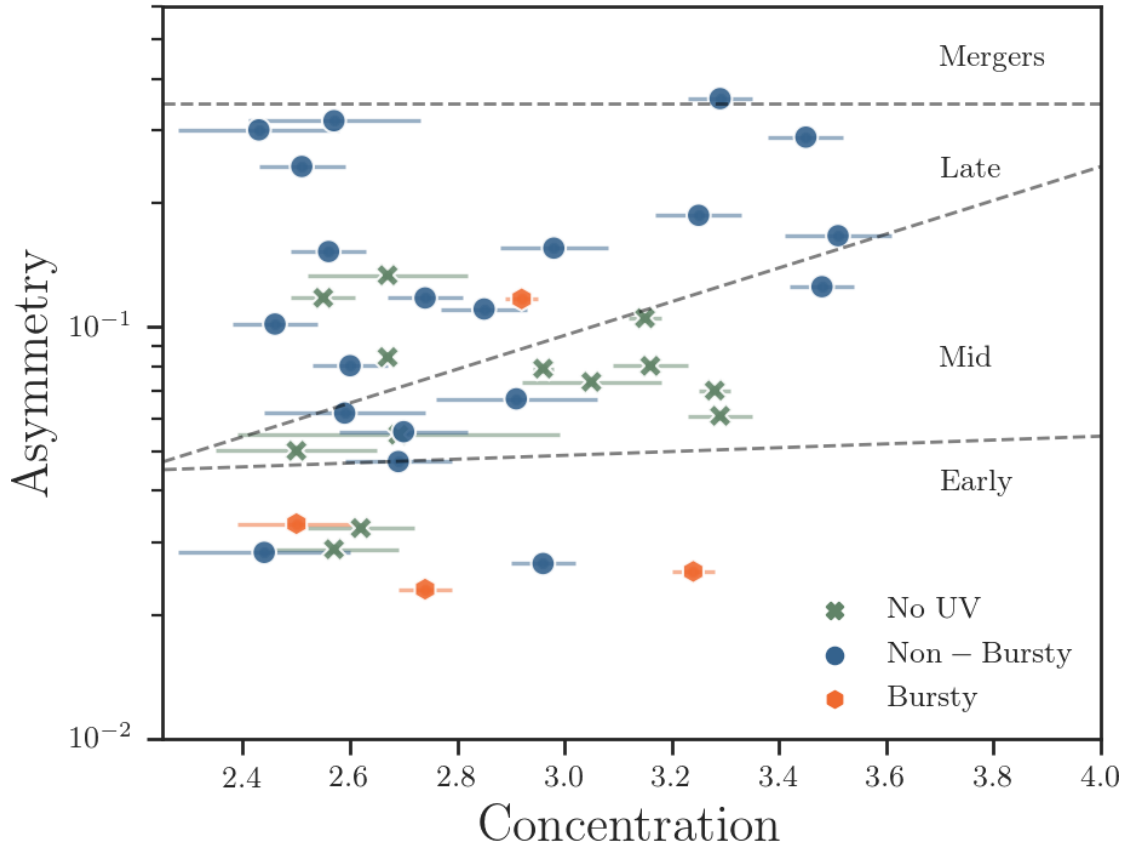


Figure 4.14: Diagram showing the concentration vs. asymmetry diagram for our sample. The points are defined in the same way as in Figure 4.12. The lines denoting the differences between various $z = 0$ systems is shown from Bershady et al. (2000). As can be seen very few to none of our systems have a morphology consistent with a system undergoing mergers.

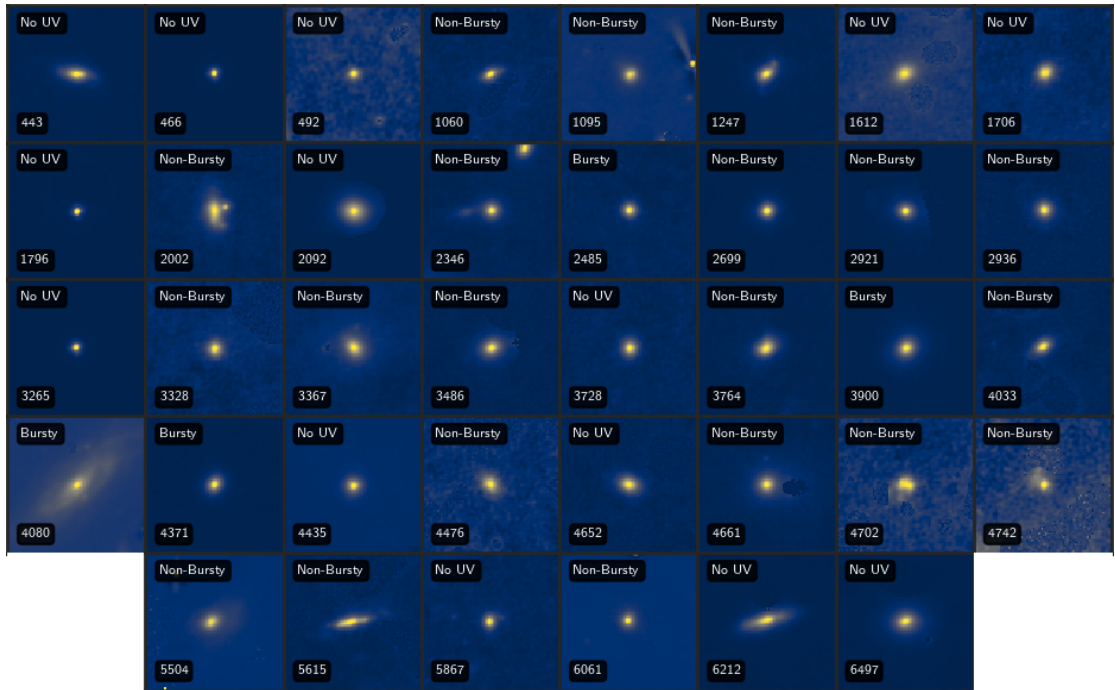


Figure 4.15: Mosaic of the 38 sources with structural and morphology measurements summarised in Table 4.3, the unique identifier of each object is shown in the bottom left corner for reference. A label using the same designation of the plots with No UV/Non-Bursty/Bursty is shown in the top left. Images presented here are the input stamps used with Morfometryka, external sources were extracted and replaced with a noise matching the stamp noise level.

2013; Koyama et al., 2013) show that our selection procedure can not account for the full $\text{SFR}_{\text{H}\alpha}$ enhancement. Regardless, this is an interesting, highly star-forming population of galaxies. Some of our systems are also ‘bursts’ which we define as those with a significantly higher star formation rate measurement in the $\text{H}\alpha$ compared with the UV measured star formation rate. This is due to very young starburst which we show can be reproduced in models with young star-formation events of a few Myr. Therefore we have discovered that some of these galaxies are indeed having their star formation triggered.

One issue that we have not discussed in any detail in this Chapter yet is that most of our objects are within the cluster environment (only 4 of the 42 objects meeting our selection criterion are found in the parallel fields). As Figure 4.7 shows, the distribution of our galaxies is such that many of them are within the A0370 cluster. This cluster is at the redshift of our sources and it is likely that these galaxies are within the cluster itself. The fact that we see more of these systems within a cluster than without might be the result of just having an overdensity in clusters compared to field galaxies, with a steeper slope mass function (e.g. Penny & Conselice, 2008). However, it is worth considering that the cluster environment produces or influences the star formation within these galaxies, in particular for the bursts. As can be seen from the image in Figure 4.7 many of our bursts are near larger galaxies. This may be a sign that interactions, even perhaps high-speed ones such as galaxy harassment (e.g. Moore et al., 1998) are producing this affect. Similar results are found by Stroe et al. (2017) in which higher densities of $\text{H}\alpha$ emitters are found in merging clusters over more relaxed systems. Further, Dressler & Gunn (1983) found signatures of increased star formation in the spectra of cluster galaxies, thought to be induced by ram pressure and later confirmed by the simulations of Bekki & Couch (2003). More recent simulations propose large-scale, low pressure shocks induced by merger processes could trigger star formation in

cluster galaxies (Roediger et al., 2014).

When we examine the morphologies of our galaxy sample (Figure 4.13) we find that most of them appear to be disk-like, which is consistent with their low stellar masses and previous studies (see Paulino-Afonso et al., 2017). One of the burst galaxies appears to be a spiral (ID:4080), which may have recently fallen into the cluster, but the other three do not seem to have any detailed substructure. However, as we show and discuss in Section 4.4.5, these systems are very compact for their mass. Compared to the size-mass relation, they fall well below the radii values seen in fields and cluster populations at the same stellar mass (Figure 4.12), as well as $H\alpha$ emitters at $z = 0.4$. We conclude that therefore these systems are likely in some type of evolutionary stage whereby very small galaxies are undergoing rapid star formation, possibly due to the cluster environment triggering this. On the other hand they could be galaxies stripped of mass by the cluster environment, but it is unlikely that this process would be efficient enough to produce so many systems. Future observations of these galaxies, through e.g., spectroscopy, should help us to better understand the origins of these systems.

4.6 Conclusions

In this Chapter we investigate the selection of emission line galaxies from two of the Hubble Frontier Fields clusters using SHARDS medium-band imaging. Our Major findings are:

- I. With the full suite of SHARDS observations now available (for A0370), we carry out an investigation to discover and study emission line selected galaxies over a wide redshift range. While lacking the wide area coverage studies such as this typically require, the full set of 25 contiguous medium-band filters combined with the strong lensing potential of the Frontier Field clusters provides an essential

tool for the identification and study of line emitters. In particular, these methods provide means to sample line emitters at high redshifts, which would typically be too faint to be detected in field observations or observations carried out with smaller ground based telescopes.

II. We identify 1,098 candidate emission-line galaxies based on a modified version of a well established two-parameter selection criterion. SHARDS photometry is calibrated to match HST images and used to update photometric redshift estimates and stellar population parameters.

III. We discover 38 predominantly low-mass $H\alpha$ emitters (average mass of $\log(M_*/M_\odot) = 8.5$). After correcting for dust extinction and $[N II]$ line contamination, we derive $H\alpha$ -based star formation rates. 27 of these candidates have corresponding HST UV data which enables investigation of potential bursts of star formation in our galaxies' recent histories. All of these $H\alpha$ emitters are undergoing star formation at high enough values such that these galaxies fall above the main sequence relation between star formation and stellar mass.

IV. We investigate bursty star formation histories using different star formation indicators that trace different time scales. We find a significant enhancement (> 0.3 dex) of $SFR_{H\alpha}$ over that of SFR_{UV} for 4 of our candidates. This fact, implies a recent burst in star formation within these systems.

V. Enhancements in the $H\alpha$ SFR are typically attributed to bursty star formation, but can also result from young population of galaxies. In order to differentiate we compare the $H\alpha$ and UV sSFR to the evolutionary tracks of two model galaxies. We find no reason to favour a young first generation population for the majority of our sample, but note that up to 10% of our galaxies show a tentative indication of young ages over bursty star formation histories.

We conclude that SHARDS imaging, combined with the HFF-DeepSpace data

set, can successfully identify emission-line galaxies over a wide range of redshifts. Future work will investigate the higher redshift emitters in a similar way. These methods, coupled with the strong lensing potential of the Frontier Fields clusters, enables the identification of a population of low-mass faint galaxies likely undergoing a burst in star formation.

Chapter 5

Escape Fractions of Merging Galaxies

This chapter utilises the selection of emission line galaxies in Chapter 4 to study the escape of Lyman continuum radiation at $2 < z < 3.5$. Using deep multi-band Hubble UVIS imaging we place upper limits on the flux of escaping ionizing photons and investigate stacked data. Further, we implement a non-parametric merger classification procedure in an attempt to gain some insight into the nature of the galaxies within the sample.

5.1 Introduction

The Universe started off as a hot plasma, later cooling to form the first atoms via nucleosynthesis, mostly consisting of hydrogen, some helium and a smaller fraction of lithium. These atoms were neutral, that is, they were formed of a combination of protons and neutrons only, with electrons remaining free of atoms. Roughly 370,000 years after the Big Bang, the universe had cooled enough such that the electrons combined with nuclei to form a neutral atomic gas that is more or less opaque to electromagnetic radiation. Today we know that the Universe is once again, for the most part, ionized. The large number of photons which have been

emitted by stars and AGN have produced a universe that is now transparent and in which the average hydrogen atom is ionized. The era in which the bulk of this transition occurred is known as the epoch of reionization (EoR). Its history, and the physical processes responsible for it are a major field of astronomical investigation (e.g. Ouchi et al., 2010; Robertson et al., 2013; Duncan & Conselice, 2015).

We have some insights into how this process of transition developed based on both the spectra of distant quasars at $z > 6$, and the properties of the cosmic microwave background. Quasar spectra show that there is significant absorption in light emitted from $z > 6$ QSOs below the Lyman-limit - the energy limit in which photons are able to ionize hydrogen (e.g. Fan et al., 2006), also known as the Gunn-Peterson effect. This puts a lower limit on reionization as occurring at $z > 6$. The upper limit of this epoch can be reached by investigating the Thompson scattering of electrons seen as radiation from the cosmic microwave background.

The latest Planck results (Planck Collaboration et al., 2018b) suggest that this reionization of the Universe happened relatively fast and late, with a mid-point redshift of $z = 7.7 \pm 0.7$. These results are consistent with theories whereby reionization is driven primarily by massive stars and active galactic nuclei (AGN) in low-mass ($\log(M_*/M_\odot) < 8$) galaxies (e.g. Robertson et al., 2015; Parsa et al., 2018). On the other hand, the empirical models of Naidu et al. (2020) predict that $< 5\%$ of massive galaxies ($M_{\text{UV}} < -18$ and $\log(M/M_\odot) > 8$) could account for more than 80% of the reionization budget, consistent with recent observations of Lyman continuum leakers exhibiting high star-formation surface densities (e.g. Matthee et al., 2018; Vanzella et al., 2018; Rivera-Thorsen et al., 2019). However, at the current time we lack precise, direct measurements of the amount of ionizing photons escaping from galaxies of different masses (especially for those of lower mass).

These low-mass galaxies within the EoR are difficult to study due to their

faintness, and the opacity of the intergalactic medium (IGM) at high redshifts (e.g. Vanzella et al., 2018). Searches for these systems are often aided by the strong gravitational lensing powers of galaxy clusters (e.g. Bhatawdekar et al., 2019). Galaxy samples are still however often biased towards the most luminous sources whose light is able to permeate through the high column-density IGM, typically consisting of bright quasars or galaxies exhibiting strong Lyman-alpha emission. It therefore remains possible that the faint galaxies responsible for reionization have yet to be discovered.

Recent works have suggested that star-forming galaxies alone may not be sufficient to drive reionization (e.g. Finkelstein et al., 2015; Livermore et al., 2017). With new optical depth estimates from Planck (Planck Collaboration et al., 2018b), the need for a large ionizing background at high redshifts is reduced. Combined with the discovery of early ($z > 4$) populations of faint AGN (Glikman et al., 2011; Giallongo et al., 2015), this has prompted a reassessment of the contributors of cosmic reionization. Observational (Giallongo et al., 2015; Madau & Haardt, 2015) and theoretical studies (Yoshiura et al., 2017; Torres-Albà et al., 2020) have shown that AGN are able to provide a significant source of ionizing flux, while investigations of known Lyman continuum leakers indicate potential AGN components (e.g. Jia et al., 2011; Prestwich et al., 2015; Kaaret et al., 2017; Grazian et al., 2018).

As well as the internal feedback from AGN and star formation, external influences such as the galaxies merger history can play a crucial role in the production of escaping ionizing photons. This is particularly important in low-mass halos (e.g. Chen et al., 2014) in which a merger event can readily expel large fractions of gas from the ISM, resulting in lower column densities in which ionizing radiation can propagate more freely. For more massive galaxies, it has even been shown that fast accretion shocks associated with gravitational infall of baryons due to events

such as mergers can contribute to hydrogen reionization (e.g. Dopita et al., 2011; Wyithe et al., 2011).

In the last few decades, significant effort has gone into searching for sources of escaping Lyman continuum radiation over various redshifts, but the majority of studies report non-detections, yielding mostly upper-limits for individual sources. At low redshifts ($0 < z < 3$); Leitherer et al. (2016) and Puschig et al. (2017) report detections in local starbursts, while a number of compact star-forming galaxies selected for high nebular oxygen ratios have been shown to exhibit non-negligible escape fractions (e.g. Izotov et al., 2016; Verhamme et al., 2017), and have even been found within the epoch of reionisation (see Matthee et al., 2018). Interestingly, galaxies selected for their high nebular oxygen ratios have been found to be strong Lyman-alpha emitters (LAEs) with high Lyman-alpha escape fractions (Nakajima et al., 2020). At intermediate redshifts, Bian et al. (2017) detect Lyman continuum (LyC) emission from a gravitationally lensed compact dwarf galaxy, A2218-Flanking at $z \approx 2.5$. Similarly, Rivera-Thorsen et al. (2019) find leaking LyC emission from a star-forming region within what they call "the Sunburst Arc" at $z = 2.4$.

At higher redshifts light from foreground galaxies along the line of sight can be a significant source of contamination (e.g. Bridge et al., 2010; Siana et al., 2015) while high-opacity IGM makes individual measurements challenging. However, it is possible to place constraints on reionization through the study of galaxy populations while making assumptions about the IGM clumping factor. Finkelstein et al. (2012) put limits on the escape fraction by investigating the luminosity density of a sample of 483 $z = 6 - 8$ galaxies selected from the CANDELS fields (Grogin et al., 2011; Koekemoer et al., 2011). The CANDELS data is also used by Grazian et al. (2012) to look at the size-luminosity relation of 153 Lyman break galaxies (LBGs) at $z \sim 7$ in order to infer limits on their contribution to

reionization. These high redshift studies typically find that the luminosity function of star-forming galaxies must extend down to $M_{UV} \sim -13$ in order to fully reionize the universe by $z = 6$.

To circumvent some of these issues, we examine lower redshift analogues of the galaxies thought to play a key role in the reionization of the universe. However, this does not come without its challenges. These dwarf galaxies, while the most abundant type of galaxy in the Universe, are difficult to detect due to their low-mass and luminosity, which both contribute to their low surface brightness. Developments in data analysis techniques and deep survey strategies have helped to provide a further insight into this population via group/cluster (e.g. Ferrarese et al., 2012; van Dokkum et al., 2015; Kondapally et al., 2018) and field (e.g. Leisman et al., 2017) studies.

Studies of emission line, star-forming galaxies have been successful in setting limits on the Lyman continuum escape fraction. At $z \sim 1$, Rutkowski et al. (2016) select a sample of ~ 600 low-mass ($\log(M_*/M_\odot = 9.3$) $H\alpha$ emitters to constrain the escape fraction to $< 2\%$. At $z = 2 - 2.5$, Rutkowski et al. (2017) and Matthee et al. (2017) find upper limits of 6% , while the work of Siana et al. (2015) and Japelj et al. (2017) find escape fractions of $< 21\%$ at $z = 3 - 4$. These analogue galaxies at redshifts $z \approx 3 - 4$ are within the ideal range for the identification of LyC emission (e.g. Steidel et al., 2018). At $z \gtrsim 3$, the Lyman-limit is redshifted into the rest-frame U-band, where the sky background is darkest and the atmosphere is transparent, allowing for observations from ground-based telescopes. These sources also benefit from low IGM opacities. Still, only a few LyC emitters have been identified at these redshifts (de Barros et al., 2016; Shapley et al., 2016; Vanzella et al., 2016) as searches are complicated by low redshift interlopers which can result in false detections, requiring high resolution imaging and spectroscopy for confirmation. Further complications arise as a result of the Lyman break selection technique

potentially excluding objects exhibiting emission in the Lyman continuum.

In order to establish how important these sources are as a driver for reionization, it is necessary to determine the fraction of ionizing radiation that is able to escape the high column density H I gas surrounding these galaxies. This can be achieved by measuring the escape fraction, f_{esc} (Steidel et al., 2001), a parameterization of the fraction of Lyman continuum ionizing photons not absorbed by the dusty interstellar medium (ISM) surrounding young stars, which then become available to ionize the neutral hydrogen in the IGM. The best method for estimating escape fractions is via a linear relation with the rest frame equivalent width (EW) of the Lyman alpha emission line (Steidel et al., 2018), however when this is not available the ratio of ionizing to non-ionizing continuum flux (900Å and 1500Å respectively) is typically used.

As such, in this Chapter we measure the escape fractions for a sample of emission-line galaxies identified via medium-band observations, utilising the strong lensing features of two of the Hubble Frontier Fields clusters. Our data is unique in that our sources are found in very deep medium-band imaging from the SHARDS-FF survey obtained with the Gran Telescopio de Canarias (GTC), and with follow-up UV imaging from the Hubble Space Telescope. Using this data, we determine the escape fraction of galaxies in our sample, placing upper limits on sources without direct detections. Furthermore, we implement non-parametric morphology measurements to identify potential mergers and investigate the effects of these physical processes on the escape of ionizing radiation.

In Section 5.2 we provide an overview of the observations and ancillary data, as well as details of the medium-band selection procedure. We calculate escape fraction upper limits for stacked, and individual sources and detail our merger classification in Section 5.3. Finally, we summarise our main results and draw conclusions in Section 5.4 and 5.5.

5.2 Observations and Data Reduction

The present analysis is based on new medium-band observations of two of the Hubble Frontier Fields (HFF) galaxy clusters (Lotz et al., 2017), Abell 370 and MACS J1149.5+2223 and their corresponding parallel fields. We couple these medium-band observations with the multi-wavelength photometric catalogues made available through the HFF-DeepSpace project (Shiple et al., 2018). Full details of the data reduction and calibration steps are provided in Section 4.2.

5.2.1 Lensing Magnification

In order to provide accurate estimations of stellar mass and luminosity derived properties, the strong gravitational lensing effects induced by these massive galaxy clusters need be accounted for. For this, reliable lensing models are required. Fortunately, for each of the six HFF clusters seven independent teams have undertaken extensive work to produce lens models, each employing various methods and initial assumptions. The magnification factors derived from these models are provided in the HFF-DeepSpace dataset and full details of their derivation can be found in Section 5.5 of Shipley et al. (2018). For further information on the lensing models, we refer the reader to the MAST website¹. To demagnify stellar masses and exclude any outliers, we take the median magnification factor (μ , provided in Tables 5.2 and 5.3) from all of the lens models available in the HFF-DeepSpace data. We find an average magnification for the sample of 4.08 ± 0.34 . All stellar mass values presented in this Chapter have been demagnified, unless otherwise stated.

¹<https://archive.stsci.edu/prepds/frontier/lensmodels/>

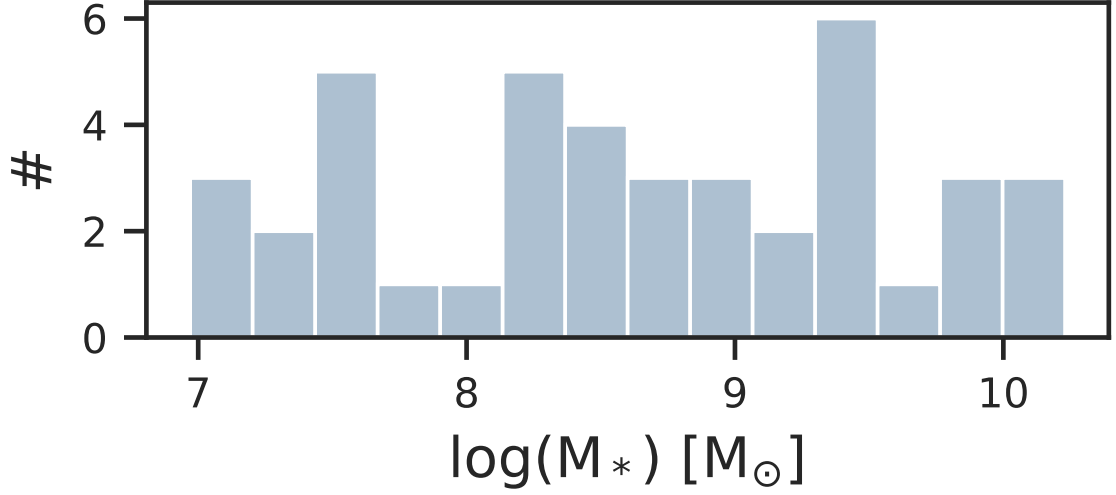


Figure 5.1: Demagnified stellar mass distribution of LyC emitter candidates. Stellar masses have been corrected for lensing magnification and are obtained using our updated photometric redshifts and FAST SPS modelling, implementing all SHARDS medium-band photometry with HFF-DeepSpace catalogues.

5.2.2 Selection of Line-Emitters

The selection of line emission candidates is detailed in full in Section 4.3. In order to select Lyman Continuum emitting candidates from our sample, we utilise HST/UVIS observations available in the HFF-DeepSpace dataset; this includes the filters: F225W, F275W and F336W for the M1149 cluster, but is limited to only F275W and F336W for the A0370 cluster (note that these data are not available for the parallel fields). These filters permit an escape fraction search over the redshift range $z \approx 2 - 3.5$, yielding a total of 62 candidate emission line galaxies. In Table 5.1 we provide a full breakdown of the redshift ranges and candidate number counts. Mass and redshift distributions of candidate galaxies are shown in Figures 5.1 and 5.2 respectively.

Selected emission lines

The combination of available HST/UVIS data and our medium-band selection method provides the unique opportunity to probe a population of low-mass

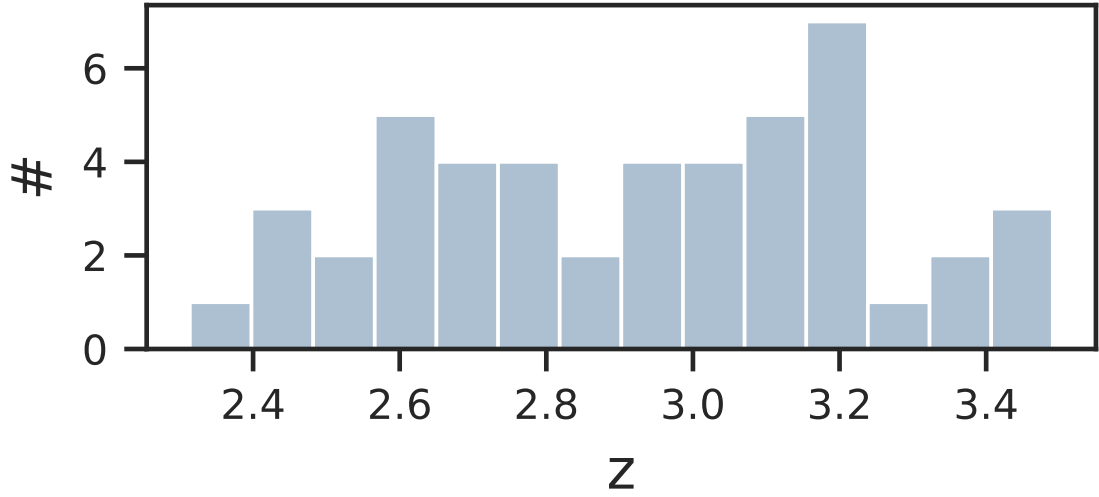


Figure 5.2: Redshift distribution of LyC emitter candidates. Photometric redshifts are obtained with EAZY with the inclusion of all SHARDS medium-band photometry with HFF-DeepSpace catalogues.

Table 5.1: Number counts and redshift range for initial Lyman continuum emitting candidates.

ionizing (LyC)	Non-ionizing (UV)	Redshift Range z	# Candidates	
			M1149	A0370
F225W	F475W	2.1 - 2.58	7	-
F275W	F606W	2.38 - 2.9	7	23
F336W	F606W	3.06 - 3.5	4	21

($\log(M_*/M_\odot) = 7 - 9$), compact galaxies between $2 < z < 3.5$. In order to identify the emission line(s) responsible for the observed flux excess, we use the combination of medium- (SHARDS) and broad-band (HST) detection filters to calculate a redshift window for which the line(s) coincides. Using these redshift windows along with photometric redshift estimates of the sources, we are able to isolate the emission lines expected to be observed. With the exception of galaxy ID:1629, which is selected by the $\text{Ly}\alpha$ 1216Å line, our sample is expected to be serendipitously identified via lines typically present in the galaxies thought to be analogues of those which contribute significantly to reionization at $z > 6$. These lines, such as N V 1240Å, C III] 1909Å and Mg II 2798Å are not only present in AGN (with EWs > 20 , e.g. Peterson, 1997; Dietrich et al., 2002), but also in low metallicity star-forming regions where hard spectra from low metallicity stars can excite the higher ionization lines. Thus, our sample not only provides a method for identifying faint, low-mass galaxies, but also finds those which are likely hosts of systems whereby the physical processes directly responsible for the enhancement of escaping LyC photons.

We take this opportunity to note that without spectroscopic follow up it is difficult to exactly identify the appropriate emission line(s) responsible for the observed flux excess at these redshifts. This is beyond the scope of this work and as such, we make no inferences about the properties of our sample galaxies based on this selection.

5.3 Results

5.3.1 LyC Escape Fraction Formalism

The UV escape fraction of high redshift galaxies can be derived from differential measurements of the ionizing (LyC, $\lambda_{\text{rest}} \leq 912\text{\AA}$) compared to non-ionizing (UV,

$\lambda_{\text{rest}} \simeq 1500\text{\AA}$) emission. However, as the intrinsic spectral energy distribution (SED) of galaxies is not typically known, and the LyC from young stars is readily attenuated through the ISM and IGM, relative escape fractions are usually derived from observations while making assumptions on the intrinsic flux ratio. The relative escape fraction, $f_{\text{esc}}^{\text{rel}}$, was first introduced by Steidel et al. (2001) and is defined as the fraction of escaping LyC photons divided by the fraction of escaping non-ionizing (UV) photons. Following Siana et al. (2007), the relative escape fraction can be derived from observed flux density ratios $(f_{\text{UV}}/f_{\text{LyC}})_{\text{obs}}$ via the equation:

$$f_{\text{esc}}^{\text{rel}} = \frac{(f_{\text{UV}}/f_{\text{LyC}})_{\text{int}}}{(f_{\text{UV}}/f_{\text{LyC}})_{\text{obs}}} \exp(\tau_{\text{IGM}}) \quad (5.1)$$

where $(f_{\text{UV}}/f_{\text{LyC}})_{\text{int}}$ is the intrinsic flux ratio and $\exp(\tau_{\text{IGM}})$ is the inverse of the redshift-dependent IGM attenuation of LyC by neutral H I.

5.3.2 Individual limits

Using the methods outlined in Section 5.3.1 we measure relative escape fractions for emission line selected galaxies in two of the frontier fields clusters at $2 < z < 3.5$. We successfully measure rest-frame ionizing flux densities of more than 2σ significance in just two galaxies from our sample (as we will discuss below in Figure 5.6), suggesting at a very tentative detection of leaking Lyman continuum emission.

In order to measure the escape fractions of individual galaxies we utilise the calibrated images provided in the HFF-DeepSpace dataset. These images are cleaned of cosmic rays, background subtracted, PSF matched and the brightest cluster galaxies have been modelled out. We utilise all available HST/UVIS (F225W, F275W and F336W with 1σ depths of ~ 29 mag) bands and select complementary imaging in the F475W and F606W bands in order to sample the non-ionizing emission at the rest-frame UV wavelength of $\lambda \sim 1500\text{\AA}$. We define

redshift ranges such that the Lyman-limit falls outside of the filters bandpass, this is necessary in order to avoid contamination by non-ionizing emission in LyC measurements. For full details of the filter combinations and redshift ranges please see Table 5.1.

We analyse all galaxy images by eye in order to check for sample contamination. We find a total of 20 false-positive interlopers, including sources which fall outside of the HST/UVIS pointings and those with a bright nearby object. Initially, we take total flux values from the HFF-DeepSpace catalogues for the corresponding bands, in which the well calibrated multi-wavelength photometry provides a robust estimate for LyC-to-UV flux ratios. The HFF-DeepSpace photometry is performed in SExtractor dual image mode using a deep, stacked detection image created from the F814W, F105W, F125W, F140W and F160W bands (see Shipley et al., 2018, for more details). However, in the majority of cases we find non-detections of LyC flux within the catalogue. Instead, we utilise the segmentation maps from deep detection images (taken from the HFF-DeepSpace dataset) to mask objects and obtain reliable background estimates, from which 1σ upper flux limits are estimated.

It can be argued that, as LyC photons may be emitted from sub-regions of a galaxy, the LyC flux may not be cospatial with the non-ionizing emission or rest-frame UV flux within a galaxy (Nestor et al., 2011). Because of this, the LyC emission should always be associated with non-ionizing emission, as described in Vanzella et al. (2012). Thus, in order to obtain accurate flux ratio estimates, we conduct measurements within the same spatial region of the ionizing, and non-ionizing images. As all images are matched in pixel scale and PSF, we map isophotes from the deep detection images to the measurement images in order to obtain spatially correlated isophotal fluxes over both, LyC and UV bands.

Ideally, intrinsic flux ratios $(f_{UV}/f_{LyC})_{int}$ need to be modelled for each galaxy

individually, where values typically range between 2-10. However, as the intrinsic ratio is sensitive to a galaxy's physical properties, such as metallicities, stellar ages and star formation histories (SFHs), here we assume a value of $(f_{UV}/f_{LyC})_{int} = 3$ in order to provide a direct comparison of our results to the literature. This estimate has been shown to be appropriate for a young ($\sim 10^7$ yr), stellar population of solar metallicity (Rutkowski et al., 2016). We note that low-mass galaxies are expected to be extremely metal poor ($< 0.1Z_{\odot}$) such that $(f_{UV}/f_{LyC})_{int} < 3$ (e.g. Bouwens et al., 2016; Ceverino et al., 2019). However, it has been shown that the amplitude of the Lyman break does not change significantly down to these metallicities, with intrinsic flux ratios dropping only as low as ~ 2 (e.g. Leitherer et al., 1999; Inoue et al., 2005).

Neutral hydrogen clouds along the line-of-sight to high redshift galaxies can significantly affect the measured UV fluxes through both continuum and Lyman line absorption. To correct for IGM absorption, τ_{IGM} , we adopt the Inoue et al. (2014) model constructed using simulations based on observational statistics of the column density and redshift distribution of the Lyman-alpha forest (LAF), Lyman limit systems (LLSs), and damped Lyman-alpha systems (DLAs).

To use this, we carry out Monte Carlo (MC) simulations of IGM absorption, simulating 1,000 sight lines at the redshift of each candidate as shown in Figure 5.3. The mean IGM transmission can then be estimated from the resulting probability distribution, convolved with the corresponding LyC filter bandpass. We use these values of IGM transmission along with the observed flux ratio, $(f_{UV}/f_{LyC})_{obs}$, in order to estimate the escape fraction via Equation 5.1.

We find only two galaxies in our sample with escaping LyC above 1σ when measuring isophotal fluxes as described above. From our sample, we would typically expect to find up to 6 galaxies by random chance above this level, therefore the reliability of these detections should first be confirmed. In order to do this, we

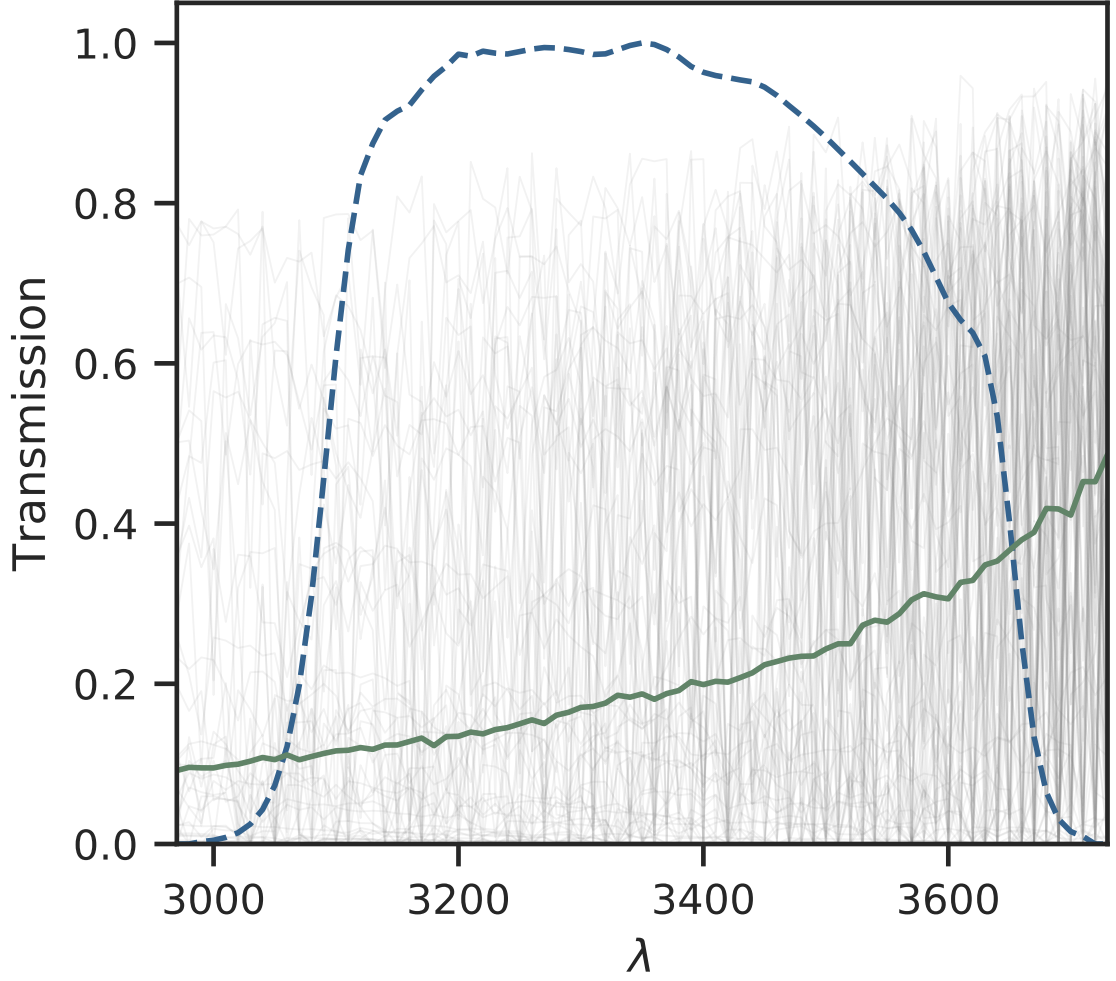


Figure 5.3: Average IGM transmission of UV light for an example galaxy at $z \approx 3$. Grey curves show the wavelength dependence of the IGM transmission for one hundred individual runs of our Monte Carlo simulations, which are based on the models of Inoue et al. (2014). The green curve shows the average IGM transmission of all 1,000 simulated sight lines, while the HST UVIS F336W filter throughput is denoted by the blue dashed line. An estimate for the value of IGM transmission is obtained through the convolution of the corresponding LyC filter response with the average IGM transmission.

obtain more accurate estimates of the significance of these sources, measuring fluxes inside a $0.2''$ radius aperture centered on the peak of the LyC flux. Following careful estimation of local background levels we find the significance of both of these sources to be $\sim 2.7\sigma$ (corresponding to a random chance of detection of roughly 1 in 300). For non-detections ($< 1\sigma$), we provide upper flux limits (1σ) based on background measurements considering only the pixels associated with the isophotes. The properties of these galaxies are summarised in Tables 5.2 and 5.3 in which we find an average upper limit for each galaxy's escape fraction within our sample of $f_{esc}^{rel} \sim 7\%$.

5.3.3 Stacked limits

In this section we discuss in more detail how we calculate our stacked limits for the Lyman continuum escape fraction. To do this, we create stacked images in both rest-frame ionizing and non-ionizing bands for the galaxies in our sample within the same HST/UVIS filter mosaics. We do not include galaxies which have individual detections when carrying out this stacking. As we are investigating galaxies over the redshifts range of $2 < z < 3.5$, simply stacking all objects in our sample would not provide robust estimates, mainly due to variations in the IGM transmission and galaxy properties at varying redshifts. Thus, we stack candidates based on the rest-frame LyC filter, limiting the redshift range, and minimising variations in τ_{IGM} . By limiting the redshift range of objects included in the stacks contributions from non-ionizing flux in LyC measurements is also reduced. We perform stacking of rest-frame ionizing flux in the HST/UVIS F275W and F336W filters, utilising the HST/ACS F606W filter for the corresponding rest-frame UV stacks, applying the procedure independently for each cluster field. The F225W band however is not used for stacking, as the data are not available for the A0370 cluster and, after interloper removal no candidates remain in our M1149 F225W

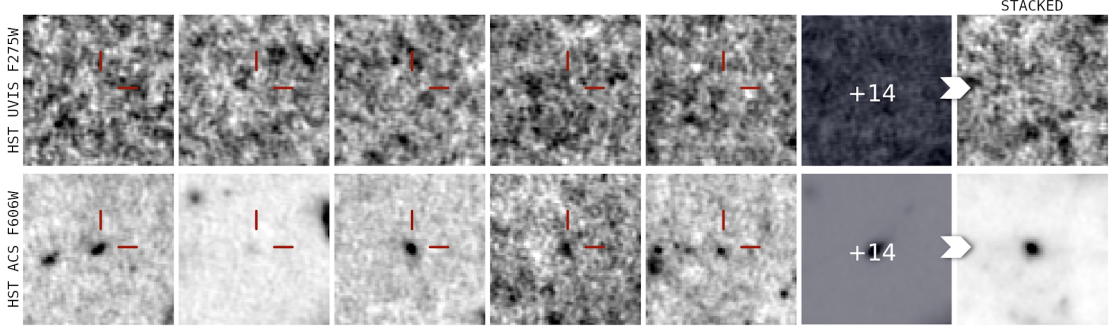


Figure 5.4: Example postage stamp cut outs and stacked images for HST UVIS F275W band objects in the A0370 cluster. The top row shows the F275W band cut outs representing the LyC at $\lambda_{\text{rest}} \leq 912\text{\AA}$. HST ACS F606W cut outs on the bottom row depict the non-ionizing flux at $\lambda_{\text{rest}} \approx 1500\text{\AA}$. The right most column shows the final stacked image, while all other columns are individual galaxies included in the stack. In total, 19 galaxies are included in the stack. All images are shown prior to cleaning however final measurements are taken after the removal of neighbouring objects and contaminants. Postage stamps are $4''$ along each side.

sample.

We initially followed a simple stacking procedure, summing all pixels in $4'' \times 4''$ postage stamps of both the rest-frame LyC and UV filters, however no significant detections are seen through this method. As described in Siana et al. (2010), variations in the sizes and morphologies of the sample galaxies can produce unreliable measurements within stacked data. For example, a strong flux measured in a pixel of one postage stamp may be compromised by noise within others where the spatial extent of the stacked galaxies can vary significantly. Therefore, we perform an optimised stacking procedure. As detailed in Siana et al. (2010), we sum only over the pixels in the LyC and UV stamps that are associated with the isophotes defined from the UV band images. This stacking procedure also provides no statistically significant detection in the LyC. We show visual examples of our stacking procedure in Figures 5.4 and 5.5 for the two A0370 cluster stacks.

As mentioned in Section 5.3.1, the nature of the IGM and the uncertain intrinsic flux ratios of the galaxies make the accurate measurement of average or limits of

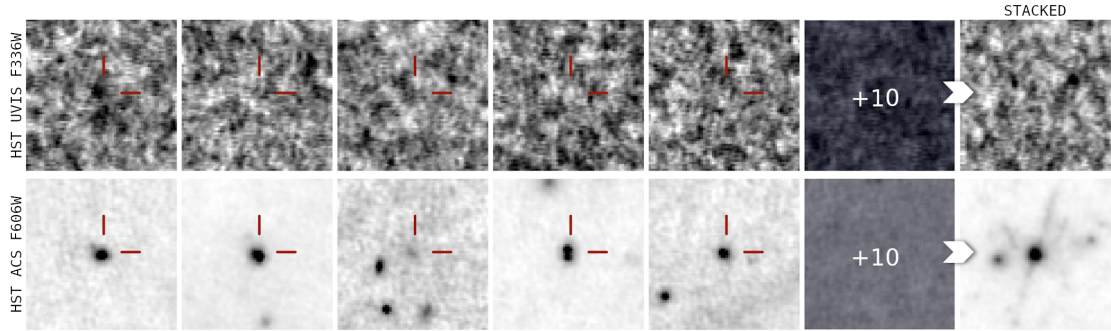


Figure 5.5: Example postage stamp cut outs and stacked images for HST UVIS F336W band objects in the A0370 cluster. Same as Figure 5.4 however top row shows the F336W band and a total of 15 galaxies are included in the stack. Postage stamps are $4''$ along each side.

escape fractions difficult. For this reason we also implement stacking procedures for measuring the limits of detections, enabling the study of properties of the galaxy sample in a more statistically significant manner. Due to the wide redshift range of our sample, we stack objects from each cluster into bins based on the available filters, providing 4 stacks in total. We do however note that due to the small sample size, particularly for the candidates identified in the M1149 imaging, stacked results may not be representative of the galaxy population as a whole.

Note however that the galaxies in our stacks have a range of lensing magnification factors. To account for this we demagnify fluxes before stacking. However, as we are only interested in the central region of the stacked images where sources overlap, we opt not to demagnify the images themselves and present our stacked values in Table 5.4.

Further, for visual inspection we apply cleaning to the images. Using the segmentation maps to isolate neighbouring sources within the postage stamps, we use a modified version of the python package `galclean`². As described in de Albernaz Ferreira & Ferrari (2018), `galclean` makes use of Astropy’s `photutils`

²<https://github.com/astroferreira/galclean>

package (Astropy Collaboration et al., 2013) to replace contaminating pixels with random values sampled from the noise, such that the images background distribution remains unchanged. The images are then stacked as previously described. However we again see no flux above background levels in the LyC stacks.

In Figure 5.7, we show the relative escape fraction (f_{esc}^{rel}) as a function of redshift for our sample. The relative escape fraction is corrected for IGM attenuation, estimated via our Monte Carlo simulations of 1,000 sight lines per object. We implement an intrinsic flux ratio of $(f_{UV}/f_{LyC})_{int} = 3$ to be consistent with literature. Tentative detections and upper limits from Tables 5.2 and 5.3 are displayed as orange points and small blue arrows respectively while stacked limits (Table 5.4) are shown as solid arrows. Additionally, we include various stacked results from the literature, spanning the entire redshift range of our sample. Our stack limits are between 1-3% for the escape fraction.

5.3.4 Merger Identification

As we would like to understand whether galaxy mergers play a role in the production of ionizing radiation (by inducing star formation, increasing gas accreted by the AGN etc), a robust classification method is needed. Because merging galaxies can display highly asymmetrical irregular morphologies, we use the Asymmetry parameter (Schade et al., 1995; Abraham et al., 1996; Bershadsky et al., 2000; Conselice et al., 2000) A , from the CAS system (Conselice, 2003) to identify if sources in our sample are likely to be galaxy mergers or not. This is one of the most robust non-parametric morphology measurement methods for finding mergers and it is often used as a way to estimate merger fractions based on a galaxies morphology (Conselice et al., 2003b, 2008; Lotz et al., 2008). In the context of mergers, the asymmetry measurement is combined with the Smoothness (Conselice, 2003), S , to define a region of the parameter space dominated by galaxy major

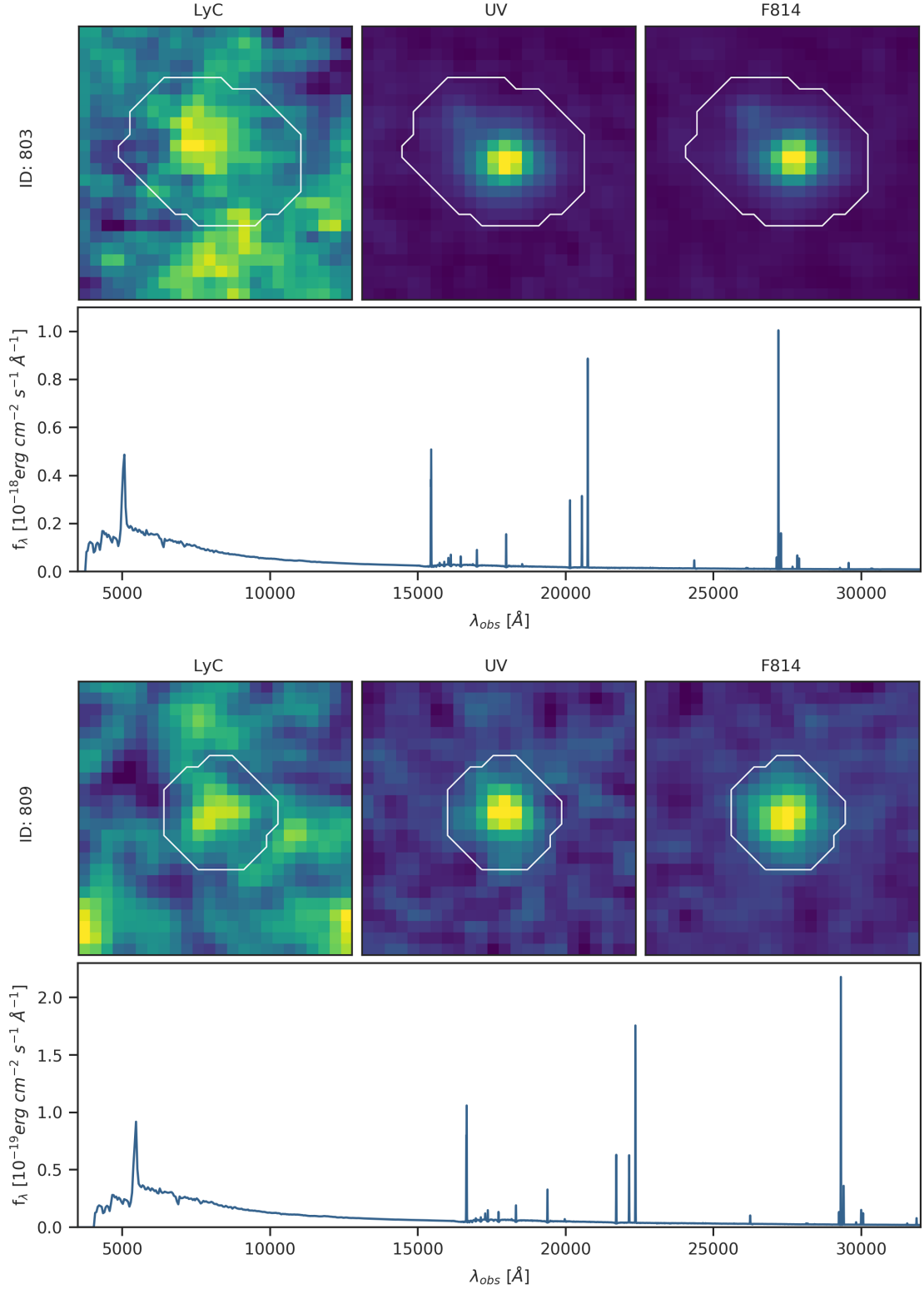


Figure 5.6: Postage stamps and EAZY SED fits for our two galaxies with flux measurements of $> 2\sigma$ in the Lyman continuum. Postage stamps show Lyman continuum (left), UV (middle) and F814W (right) and are $\sim 1.5'' \times 1.5''$ in size. We also show the EAZY SED fits for each galaxy in the observed wavelengths. 803 has a photometric redshift of $z = 3.15$ and is detected in the F517W band which corresponds to the Ly α line. 809 is at $z = 3.46$ and detected in the F941W band, likely corresponding to N II] $\lambda 2142 \text{ \AA}$ emission.

Table 5.2: Summary of individual escape fraction of emission line selected galaxies from the M1149 cluster

ID	R.A.	DEC.	z	M _{UV}	M _*	μ	A	τ_{IGM}	$f_{\text{esc}}^{\text{rel}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
F275W:									
1283	177.38723	22.38438	2.93	-19.32	9.40	1.51	0.23	0.12 ± 0.01	< 0.02
2545	177.39976	22.39301	2.89	-18.00	8.80	14.25	0.21	0.15 ± 0.01	< 0.02
4749	177.41050	22.40471	2.43	-20.39	9.50	1	0.43	0.37 ± 0.03	< 0.25
5565	177.40976	22.41252	2.98	-18.15	9.91	1.71	0.57	0.12 ± 0.01	< 0.01
F336W:									
809	177.38238	22.37989	3.46	-18.30 ± 0.24	7.81	1.04	0.12	0.09 ± 0.02	$0.03^{+0.05}_{-0.02}$
4500	177.42167	22.40612	3.48	-16.87	8.42	1.40	0.31	0.08 ± 0.01	< 0.04
4971	177.42151	22.40881	3.15	-19.81	8.29	1.33	0.36	0.23 ± 0.02	< 0.02

Table columns: (1) HFF-DeepSpace catalogue ID; (2) Right ascension in degrees; (3) Declination in degrees; (4) Photometric redshift estimated using the EAZY software, including all available SHARDS and HFF-DeepSpace bands; (5) Magnification corrected isophotal magnitude in the rest-frame UV ($\lambda_{\text{rest}} \approx 1500\text{\AA}$), HST/ACS F606W is used for all objects; (6) Magnification corrected stellar mass in units of log solar masses, estimated with FAST utilising all available bands; (7) Median magnification factor (μ) from all available lens models, when data is unavailable we set μ to 1 ; (8) Asymmetry value used for merger classification; (9) Average IGM transmission of UV light based on Monte Carlo simulations over 1,000 simulated sight lines; (10) Relative LyC escape fraction and its $\pm 1\sigma$ uncertainties, including corrections for dust and IGM attenuation. **Note:** Where escape fractions are preceded with an ‘<’, the values represent 1σ upper limits.

Table 5.3: Summary of individual escape fraction of emission line selected galaxies from the A0370 cluster

ID	R.A.	DEC.	z	M _{UV}	M _*	μ	A	τ_{IGM}	$f_{\text{esc}}^{\text{rel}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
F275W:									
1341	39.95829	-1.59271	2.73	-16.92	7.18	2.81	0.30	0.19 ± 0.01	< 0.04
1872	39.94373	-1.58733	2.62	-18.53	8.64	1	0.45	0.24 ± 0.02	< 0.06
2117	39.95892	-1.58499	2.95	-16.93	8.36	2.89	0.39	0.12 ± 0.01	< 0.03
2164	39.96706	-1.58455	2.92	-16.54	7.67	11.31	0.14	0.13 ± 0.01	< 0.03
2330	39.96161	-1.58302	2.57	-15.25	7.15	4.45	0.38	0.27 ± 0.02	< 0.16
2548	39.98755	-1.58159	2.75	-15.71	7.54	2.48	0.17	0.19 ± 0.01	< 0.08
3266	39.98290	-1.57647	2.57	-15.87	7.66	4.87	-	0.27 ± 0.02	< 0.45
3706	39.99485	-1.57280	2.61	-17.56	8.58	1.49	0.22	0.25 ± 0.02	< 0.04
3854	39.94983	-1.57175	2.66	-18.04	8.33	1	0.14	0.23 ± 0.02	< 0.03
4114	39.99397	-1.57058	2.61	-20.12	9.12	1.52	0.39	0.27 ± 0.02	< 0.03
4213	39.99166	-1.56925	2.63	-16.55	6.97	1	-	0.24 ± 0.02	< 0.20
4366	39.95659	-1.56795	2.45	-15.60	7.49	2.98	0.18	0.36 ± 0.03	< 0.11
4519	39.99003	-1.56789	2.67	-21.05	9.87	1	0.60	0.22 ± 0.02	< 0.05
4616	39.99128	-1.56780	2.85	-19.72	8.68	1	0.40	0.15 ± 0.01	< 0.05
4989	39.96107	-1.56262	2.76	-19.44	8.29	5.68	0.30	0.19 ± 0.01	< 0.01
5226	39.97361	-1.55974	3.00	-19.49	10.23	1	0.36	0.10 ± 0.01	< 0.01
5347	39.95198	-1.56308	2.44	-20.64	9.84	2.26	0.57	0.37 ± 0.03	< 0.07
5687	39.97501	-1.55618	2.82	-21.21	10.19	1	0.07	0.16 ± 0.01	< 0.02
5769	39.97072	-1.55482	2.53	-17.05	8.50	1	0.33	0.30 ± 0.02	< 0.08
F336W:									
803	39.97475	-1.59918	3.15	-18.76 ± 0.10	8.91	3.43	0.23	0.21 ± 0.02	$0.02^{+0.05}_{-0.01}$
1399	39.98341	-1.59220	3.01	-18.13	7.41	3.19	0.79	0.32 ± 0.03	< 0.05
1629	39.95825	-1.59015	3.23	-19.14	9.52	2.64	0.50	0.17 ± 0.02	< 0.04
2068	39.97426	-1.58559	3.07	-17.62	7.66	6.76	0.34	0.26 ± 0.02	< 0.04
2128	39.95285	-1.58534	3.24	-20.16	9.68	1.99	0.30	0.16 ± 0.01	< 0.01
2282	39.96371	-1.58327	3.39	-16.51	8.94	1	0.58	0.11 ± 0.01	< 0.06
2446	39.95052	-1.58232	3.06	-16.76	8.32	1	0.47	0.27 ± 0.02	< 0.29
2558	39.95363	-1.58185	3.03	-20.28	9.08	2.16	0.36	0.29 ± 0.03	< 0.02
2997	39.96986	-1.58070	3.11	-18.14	8.07	19.48	0.35	0.24 ± 0.02	< 0.02
3023	39.95382	-1.57837	3.19	-18.01	8.84	2.46	0.60	0.19 ± 0.02	< 0.02
3721	39.99461	-1.57270	3.18	-17.60	8.41	1.48	0.42	0.19 ± 0.02	< 0.08
4113	39.95380	-1.57002	3.17	-18.94	9.39	2.69	0.35	0.19 ± 0.02	< 0.02
4346	39.99053	-1.56810	3.17	-18.73	9.31	1	0.63	0.20 ± 0.02	< 0.10
4620	39.99227	-1.56928	3.49	-20.67	10.02	1	0.15	0.08 ± 0.01	< 0.01
4797	39.99221	-1.56393	3.07	-18.90	9.31	1	0.13	0.26 ± 0.02	< 0.04
5157	39.96892	-1.56041	3.22	-17.20	7.30	1	0.05	0.18 ± 0.02	< 0.09

Table columns: Same as 5.2

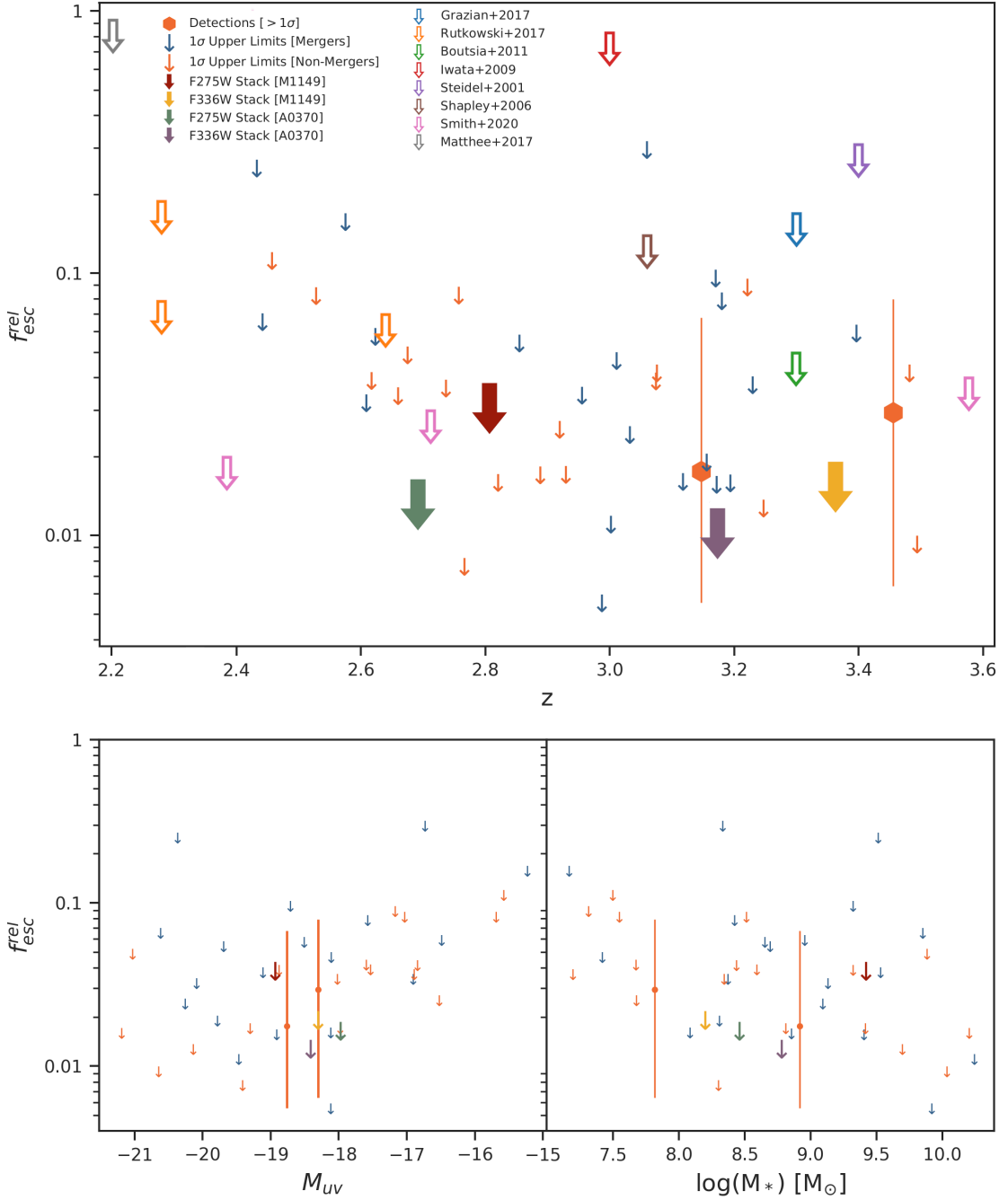


Figure 5.7: Relative escape fractions as a function of redshift (top), M_{UV} (bottom left) and demagnified stellar mass (bottom right). The orange points represent individual galaxies in which we have obtained flux measurements of more than 1σ significance in the LyC images (tentative detections), while 1σ upper limits for the remainder of the sample are shown by small blue and orange arrows (non-detections) for mergers ($A \geq 0.35$) and non-mergers ($A < 0.35$). The properties of these individual measurements are detailed in Tables 5.2 and 5.3. Large filled arrows show the results of the stacking procedures as detailed in Table 5.4. Empty arrows show stacked results from the literature spanning the entire redshift range of our sample (Steidel et al., 2001; Shapley et al., 2006; Iwata et al., 2009; Boutsia et al., 2011; Grazian et al., 2017; Rutkowski et al., 2017; Smith et al., 2020).

Table 5.4: Summary of escape fractions for stacked images

Cluster	Filter	N_{obj}	z	M_{UV} [mag]	M_* [$\log(M_*/M_\odot)$]	μ	τ_{IGM}	f_{esc}^{rel}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
M1149	F275W	4	2.81	-18.97	9.40	4.62	0.19	< 0.04
M1149	F336W	2	3.36	-18.34	8.18	1.37	0.13	< 0.02
A0370	F275W	19	2.69	-18.01	8.44	2.67	0.22	< 0.02
A0370	F336W	15	3.17	-18.45	8.76	3.26	0.21	< 0.01

Table columns: (1) Cluster field from which objects have been identified; (2) Filter used for stacking; (3) Number of galaxies in stack; (4-8) Same as Tables 5.2 and 5.3, values are calculated as the mean of all corresponding stacked objects; (9) 1σ upper limit on relative LyC escape fraction.

mergers using the following limit

$$A > 0.35, \quad A > S. \quad (5.2)$$

A captures how asymmetric the morphology of a galaxy is and S measures the contribution from high-spatial frequency structures to the flux, such as star-forming regions. The $A > S$ limit ensures that galaxies with areas of clumpy star formation do not share the same region of the parameter space with galaxy mergers. However, as we are resolution and noise-limited, S is less effective as small structure will appear kernel shaped and thus result in values for S close to zero.

For these reasons, here we only focus on merger classifications using the asymmetry (A) index, as it will capture the most important merging features at this resolution and signal to noise level and is expected to produce a more pure sample, although potentially incomplete. The Asymmetry of a galaxy image is defined as

$$A = \frac{\Sigma |I - I_{180}|}{\Sigma |I|} - A_{BG}, \quad (5.3)$$

where I is the source flux, I_{180} the source flux rotated by 180° around its centre and A_{BG} accounts for the asymmetry of the background. The background term, A_{BG} , is measured in the same way as the asymmetry but with a patch of the sky that does not overlap with the source's segmentation map.

The details of the measurement are as follows. We select the band with the highest signal-to-noise ratio for each source. This means that most measurements are done in the F606W or F814W bands. Then, we generate a segmentation map with `galclean` and replace neighbouring sources with a sampling of the background to ensure that our A measurement is not affected by it. Thus, we measure the Petrosian radius (Petrosian, 1976), R_p , axis ratio, q , using `Morfometryka` (Ferrari et al., 2015) and proceed to estimate the asymmetry of the source by measuring it within an elliptical aperture of $1.5R_p$ and axis ratio, q . Our results are presented in Tables 5.2 and 5.3 and a visualisation of the morphologies can be found in Figure 5.8, where the A value is printed in the upper left corner of each image whilst the source identification and band used for the measurement is shown in the bottom left corner.

We fail to find proper segmentation maps and Petrosian regions for the unstacked images of sources 3266 and 4213 due to low SNR. Additionally, sources 2997 and 5226 display lensed morphologies which will display high A values, regardless of being a merger or not. Finally, due to the proximity to bright sources, the source masking process done for source 2330 is not ideal and can introduce biases in the A measurement. As such, this results in measurements and merger classifications for 37 out of the 42 sources. Our selection criteria considers all galaxies above the asymmetry threshold of Equation 5.2 to be potential mergers. We find a merger fraction of $45\% \pm 11\%$ for our sample, corresponding to 17 out of 37 galaxies. This is significantly higher than other studies, but could be due to us probing lower mass galaxies that are likely more asymmetric than higher mass systems, as well

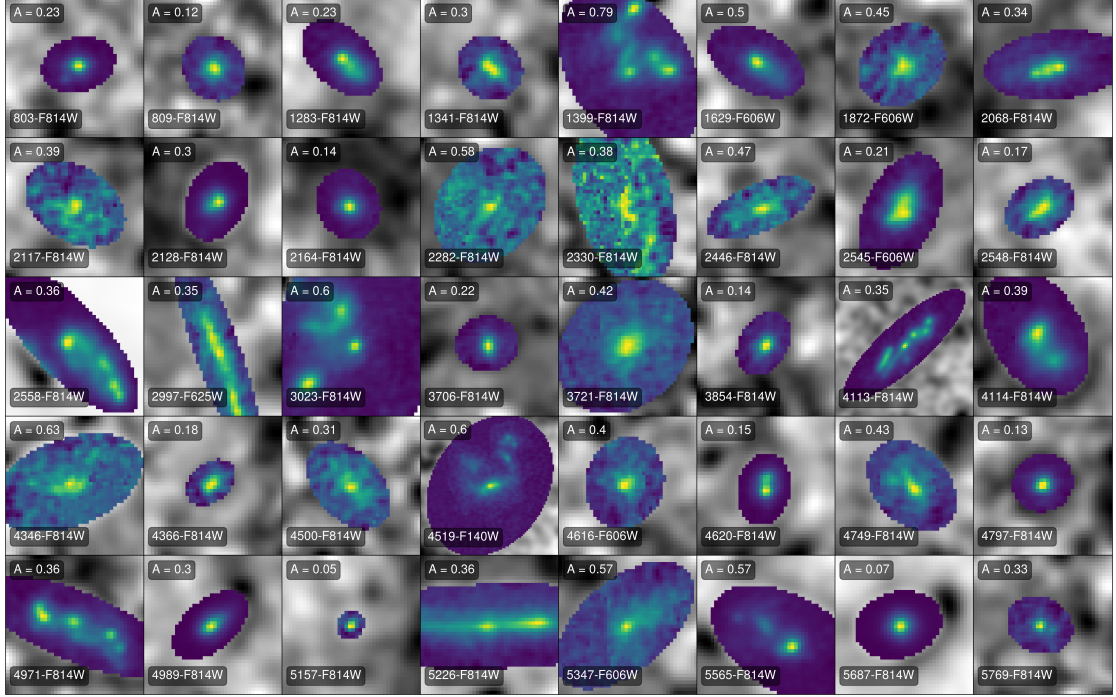


Figure 5.8: Mosaic with 40 out of 42 sources with valid Asymmetry measurements ordered by ID, sources 3266 and 4213 are not included. The Asymmetry value can be found in the upper left corner while the source identification and band used for the measurement is located at the bottom left corner. Each source image shows the Petrosian region ($1.5 R_p$) used to measure the main term of Equation 5.3 in viridis colourmap. The grey area was smoothed with a gaussian kernel only for visualisation purposes, the background term of the asymmetry, A_{BG} , is measured with the original pixel values that are beyond the Petrosian region. Sources with $A > 0.35$ are considered here to be likely galaxy mergers.

as other possible causes of large asymmetry measurements such as gravitational lensing distortions and unevenly distributed star-forming regions.

In Section 5.4.2 we discuss our findings and the likely the role of mergers in the escape of Lyman continuum emission.

5.4 Discussion

5.4.1 Implications

Our tentative detection of a measurable escape fraction for two of our low-mass systems ($M_* = 10^{7.81}, 10^{8.91}$) allows us to investigate the likelihood that low-mass dwarf galaxies are able to significantly contribute to the reionization of the universe. One way to make this measurement from our data is to consider the amount of Lyman-continuum emission coming from these systems and using standard assumptions about the structure of the high-redshift IGM (Duncan & Conselice, 2015). We find that as these galaxies produce low levels of Lyman continuum radiation along with the escape fractions measured in this work, they are unlikely to be the main drivers for reionization.

In general, predictions from theoretical models suggest that the contribution of star-forming galaxies to reionization does not correlate heavily with redshift (e.g. Gnedin, 2016; Hassan et al., 2016; Xu et al., 2016; Anderson et al., 2017). As such, we are able to compare the estimates from these higher redshifts studies to our results at $z \sim 3$. For example, the works of Xu et al. (2016) and Anderson et al. (2017) find low-mass galaxies are the dominant contributors to reionization with escape fractions that are anticorrelated with mass and M_{UV} . Xu et al. (2016) predicts escape fractions increase from $\sim 5\%$ in the mass range of 10^8 - $10^9 M_\odot$ up to 40-60% for fainter low-mass galaxies, while Anderson et al. (2017) find a power law dependence of f_{esc} on UV magnitude. At first glance, it seems that some of our observational results are in good agreement with these theoretical models, finding similar trends in both galaxy mass and UV magnitude compared to our limits as presented in the bottom two panels of Figure 5.7 and the results in Tables 5.2 and 5.3. However, as our measurements of f_{esc}^{rel} are dependent on the limiting magnitude of the LyC image (i.e. a detection threshold limit) these observed trends can be

accounted for. This brings our results in line with the simulations of Hassan et al. (2016) and Yoshiura et al. (2017) who constrain the escape fraction at relatively low values ($f_{esc} < 15\%$), independent of galaxy mass or magnitude.

While methods for estimating the escape fraction of a galaxy are fairly consistent throughout the literature, selection of candidates is often varied. Searches for escaping Lyman continuum look to star-forming galaxies discovered in wide field observations (Shapley et al., 2016; Grazian et al., 2017) and spectroscopic surveys (Steidel et al., 2018). Similarly, Steidel et al. (2001), Iwata et al. (2009) and Boutsia et al. (2011) search for combinations of LBGs and LAEs over various field and protocluster environments while studies such as Rutkowski et al. (2017) and Smith et al. (2020) use the preselection of candidates via emission line and spectroscopic redshift catalogues. Finally, recent observational evidence (Matthee et al., 2018; Vanzella et al., 2018) and simulations (Naidu et al., 2020) are driving searches towards more massive galaxies, which results suggest could account for more than 80% of the reionization budget.

Care needs to be taken in the comparison of our results to previous work, as very little research has been done on measurements of escape fractions for these types of galaxies. Typically, the relatively small fields covered by lensing clusters have not provided the sample numbers required for these types of studies and large surveys are often more favourable. However, with the combination of dedicated medium-band surveys like the SHARDS-FF, combined with the wealth of ancillary data available for the Frontier Fields clusters, the selection of large numbers of emission line galaxies at a range of redshifts is now possible.

We can however look to LyC leakers and so called ‘Green Pea’ galaxies, which are found to have similar properties (mass, morphology, metallicity etc) as luminous blue compact dwarfs as well as UV-luminous high-redshift galaxies such as LBGs and LAEs. These galaxies typically reside in low-density environments and are

ideal low-redshift analogues due to their compact size, low levels of dust reddening and strong [O III] $\lambda 5007\text{\AA}$ emission which lead to high levels of LyC production and low H I column densities (Yang et al., 2017; Nakajima et al., 2020). Further, HST imaging of these ‘Green Peas’ has shown them to exhibit low surface density features with bright star-forming regions, indicating the potential for recent or ongoing merger events (e.g. Cardamone et al., 2009).

Individual limits are not as robust as we would like due to uncertainties in IGM opacity along the galaxies sight lines, and without spectroscopic follow up intrinsic flux ratios are difficult to estimate. By assuming an intrinsic flux ratio of 3, we are able to compare our results to existing works, but note that galaxies of lower mass are expected to be extremely metal poor ($< 0.1Z_{\odot}$) such that $2 < (f_{UV}/f_{LyC})_{int} < 3$. This may also account for some of the observed trend in f_{esc}^{rel} with galaxy mass and UV magnitude.

We find the upper limits derived from our stacking of low-mass dwarf galaxies is roughly consistent with the samples of LBGs, LAEs, HAEs and SFGs (Steidel et al., 2001; Shapley et al., 2006; Iwata et al., 2009; Boutsia et al., 2011; Grazian et al., 2017; Matthee et al., 2017; Rutkowski et al., 2017; Smith et al., 2020) as displayed in Figure 5.7. We note however that as we are only able to obtain upper limits for our stacks, we can not draw any conclusions from these results.

5.4.2 Role of Merging

The emerging theoretical picture of LyC escape is that feedback carves holes through the ISM (Ma et al., 2016; Trebitsch et al., 2017, and references therein). These chimneys of very low H I column densities are the channels through which LyC photons can escape from galaxies at high- z . AGN feedback may also form these holes by powerful outflows as observed in more massive galaxies (Genzel et al., 2014).

This feedback can further be enhanced by processes such as mergers, in which a galaxies internal H I reservoirs can be sufficiently disturbed such that photons which are usually attenuated by the IGM are able to stream freely from the galaxy through these low column density chimneys. Additionally, merging events can lead to an increase of gas around the AGN and induce bursts of star formation, both of which can lead to the increased production of ionizing photons. Whilst there is little observational work on this in the literature, we propose that our sample, which benefits from strong gravitational lensing powers of some of the most massive galaxy clusters, provides an ideal means of investigating these effects.

We separate sources into merger and non-merger sub-samples using the Asymmetries measured in Section 5.3.4 with the imposed limit from Equation 5.2. Figure 5.9 shows the asymmetry values for each of the 37 sources as a function of signal-to-noise ratio and colour coded by stellar mass. The inner plot in Figure 5.9 displays the average escape fraction limit for the merger and non-mergers sub-samples, with 7% and 4%, respectively. We find that $45\% \pm 11\%$ of the candidates show signs of merging based on their A values. Unfortunately, merger fractions for galaxies at similar masses and redshifts for typical field galaxies do not yet exist. However, we can measure merger fractions for high mass systems, where in general the merger fraction with pairs and morphology is significantly lower than this at these redshifts (e.g. Conselice & Arnold, 2009; Duncan et al., 2019). This could be an indication that mergers are more common for our systems than a general field sample selection, however we have not ruled out the possibility that the high asymmetry levels measured are due to other physical processes.

Because we do not have a merger fraction measured for such low-mass galaxies in general these results are still tentative regarding how escape fractions are affected by the merger process. However, this warrants further investigation and quantitative analysis. This is beyond the scope of this work but we suggest that with the full set

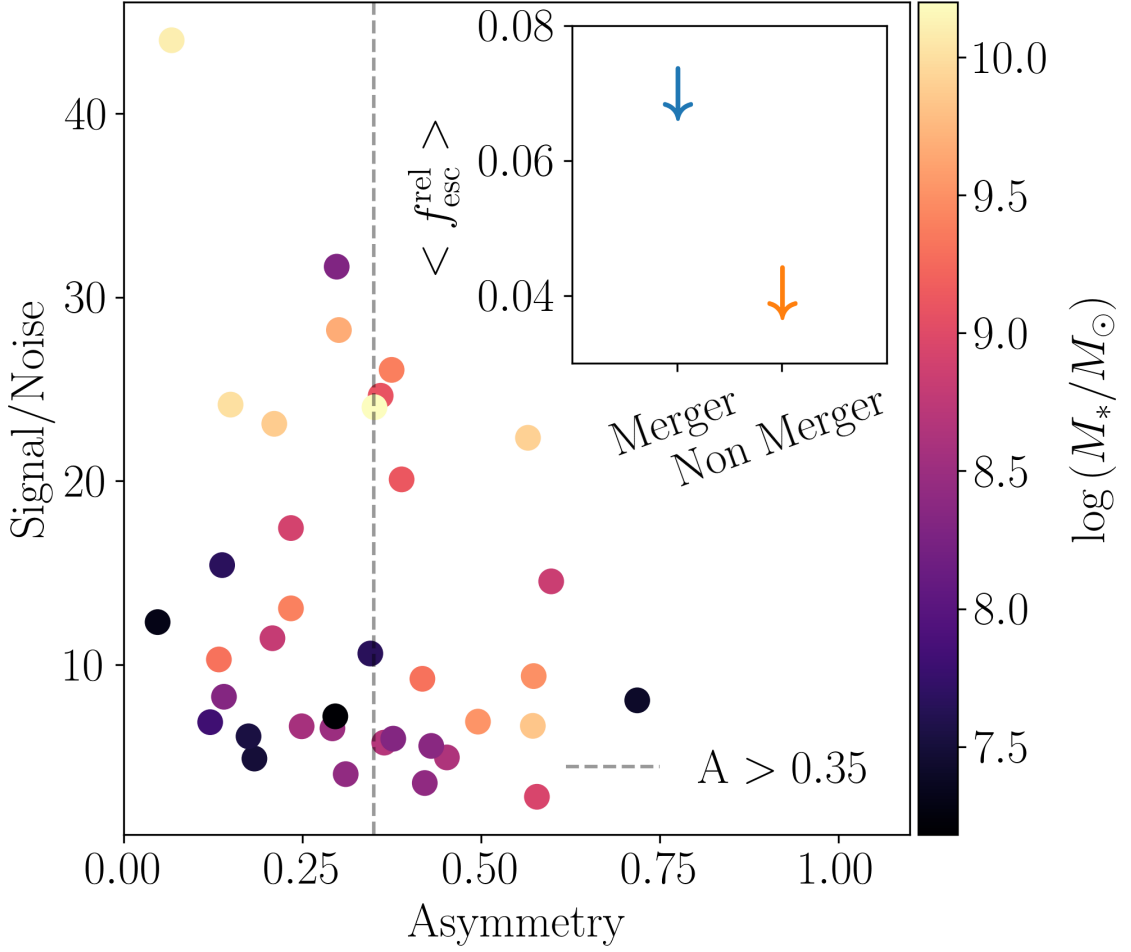


Figure 5.9: Asymmetry measurements for the 37 sources as detailed in Section 5.3.4, compared with signal-to-noise on the y-axis, and colour coded by stellar mass. The dashed gray vertical line displays the threshold used to classify a source as a potential merger following Equation 5.2. The inner plot displays the average f_{esc} limit for galaxy mergers ($A > 0.35$) and non-mergers ($A \leq 0.35$).

of SHARDS-FF observations, similar analysis to those presented in this Chapter may provide some insight into the role of mergers in the escape of ionizing photons.

5.5 Summary

In this Chapter we investigate the escape fraction for galaxies as detected in the Hubble Frontier Fields using SHARDS medium-band imaging with the GTC. Our method is a mixture of techniques that use emission lines to find sources, as well

as blue HST fields to find Lyman-continuum light. We discovered a set of 42 new line emitters in our SHARDS data and then use the Hubble Space Telescope data to probe the rest-frame UV emission from these galaxies at redshifts $z = 2 - 3.5$. Our major findings are:

I. We find that 2 of our 42 systems have a measurable (2.7σ) escape fraction. These galaxies are on the low-mass end ($M_* < 10^9$) and as such our results provide further evidence supporting the idea that low-mass galaxies are the dominant type of sources responsible for reionization.

II. We stack our 40 candidates which do not have $>2\sigma$ detections into bins based on cluster membership and the HST/UVIS band. We do not find leaking LyC in any of the stacks and instead calculate upper limits using the same methods we use for the individual galaxies.

III. The observed correlations between f_{esc}^{rel} with galaxy mass and UV magnitude can be accounted for through a combination of LyC detection threshold limits, and uncertainties in the intrinsic flux ratio at lower masses.

IV. $46\% \pm 11\%$ of our candidate emission line galaxies show signs of mergers based on our asymmetry cut. This indicates that mergers are more common for our systems than a general field sample selection when comparing to higher mass field galaxies (as merger fractions at similar masses and redshifts do not yet exist). However, contamination from highly asymmetric non-merging galaxies has not been ruled out.

Ultimately we will want to be able to examine more distant low-mass galaxies to determine if they have properties similar to ours. With JWST we will start to be able to study these galaxies in the epoch of reionization where, through investigations of sizes, metallicities and star formation rates (amongst other properties) we will be able to determine if our sources truly are the analogues of those that

reionized the Universe. Further examination of similar low-mass systems at similar redshifts will also provide more evidence for or against this idea that dwarf galaxies involved in mergers are responsible for producing the flux for reionization.

Chapter 6

Thesis Summary

In this thesis, I investigate methods of probing the epoch of reionization through the detection and examination of high redshift sources and low redshift analogues. In Chapter 2, I show that massive, compact galaxy clusters can be an effective tool for the identification of high redshift galaxies due to their strong lensing potential and low ICL fractions. Motivated by this work, in Chapter 3, I discuss the design and implementation of a novel algorithm for the optimal extraction of 2D spectra from IFU datacubes. In chapters 4 and 5, I present the study of SHARDS medium-band imaging for the identification and analysis of faint, low-mass dwarf galaxies.

6.1 Compact lensing clusters

In this chapter I presented the results of a VLT MUSE/FORS2 and Spitzer survey of a unique compact lensing cluster CLIO at $z = 0.42$, discovered through the GAMA survey using spectroscopic redshifts. Compact and massive clusters such as this are understudied, but provide a unique perspective on dark matter distributions and for finding background lensed high- z galaxies. The CLIO cluster was identified for follow up observations due to its almost unique combination of high mass and dark matter halo concentration, as well as having observed lensing arcs from ground based images. Using dual band optical and infra-red imaging from FORS2

and Spitzer, in combination with MUSE optical spectroscopy, I identify 89 cluster members and find background sources out to $z = 6.49$. I describe the physical state of this cluster, finding a strong correlation between environment and galaxy spectral type. Under the assumption of a NFW profile, I measure the total mass of CLIO to be $M_{200} = (4.49 \pm 0.25) \times 10^{14} M_{\odot}$. I build and present an initial strong-lensing model, and measure a relatively low intracluster light (ICL) fraction of $7.21 \pm 1.53\%$ through galaxy profile fitting.

I find that compact clusters such as CLIO are ideal for future follow up work in the search for high redshift galaxies. This cluster already has several high- z lensing candidates with only modest spectroscopic observations. Because of its high concentration, it is also in a unique regime for massive clusters. Due to its strong potential for lensing background galaxies and its low ICL, the CLIO cluster will be a target for the 110 hour JWST ‘Webb Medium-Deep Field’ (WMDF) GTO program.

6.2 Optimised spectral extraction

With the ever growing popularity of integral field unit (IFU) spectroscopy, countless observations are being performed over multiple object systems such as blank fields and galaxy clusters. With this, an increasing amount of time is being spent extracting one dimensional object spectra from large three dimensional datacubes. However, a great deal of information available within these datacubes is overlooked in favour of photometrically based spatial information. In this chapter I presented a novel, yet simple approach of optimal source identification, utilising the wealth of information available within an IFU datacube, rather than relying on ancillary imaging. Through the application of these techniques, I have shown that I am able to obtain object spectra comparable to deep photometry weighted extractions without the need for ancillary imaging. Further, implementing my custom designed

algorithms can improve the signal-to-noise of extracted spectra and successfully deblend sources from nearby contaminants, ideal for spectroscopic investigation of faint, high redshift galaxies thought to be responsible for the reionization of the universe.

6.3 Emission line galaxies and bursty star formation

Emission line galaxies provide a crucial tool for the study of galaxy formation and evolution. Various emission lines can provide a means to trace a galaxy's star formation history or metal enrichment, and to identify galaxies at a range of stellar masses. In this Chapter I present a study of emission line galaxies in the SHARDS Frontier Fields medium-band survey. Through detailed flux calibrations I combine the first results of the SHARDS-FF survey with existing Hubble Frontier Field data to select 1,098 candidate emission line galaxies from the Hubble Frontier Field clusters Abell 370 and MACS J1149.5+2223. Furthermore, I use this deep medium-band imaging to update photometric redshift estimates and stellar population parameters and discover 38 predominantly low-mass $H\alpha$ emitters at redshifts $0.24 < z < 0.46$. 27 of these sources have corresponding UV data from the Hubble Space Telescope which allows us to investigate the burstiness of their star formation histories. I find that more than 50% of our sample show an enhancement in $H\alpha$ over UV, suggesting recent bursts in star formation on time scales of a few, to tens of megayears. I investigate these sources and find that they are typically low-mass disk galaxies with compact sizes. Their structures and star formation suggest that they are not undergoing mergers but are bursting due to alternative causes, such as gas accretion.

6.4 Escape fractions

The fraction of ionizing ultraviolet photons which escapes galaxies at high redshifts is a key quantity for understanding the reionization of the universe but this has to be measured within lower redshift galaxies. I present a study of the escape fractions of UV photons from emission line selected galaxies as found in the SHARDS Frontier Fields medium-band survey. I have used this deep imaging survey to locate 42 galaxies over a range of masses between redshifts $2 < z < 3.5$. I use deep multi-band Hubble UVIS imaging to measure the flux of escaping ionizing photons from these systems, obtaining 1σ upper limits of $f_{esc}^{rel} \sim 7\%$ for individual galaxies, and 2% for stacked data. I measure escaping Lyman continuum flux from only two galaxies, both at a $\sim 2.7\sigma$ level. Furthermore, I implement a non-parametric merger classification procedure to find 46% of our candidates show signs of mergers based on our asymmetry cut.

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