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cluster galaxies as traced by their gas phase
metallicities ”**

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Abstract

Aims. Gas-phase metallicities offer a deep insight into the chemical evolution of galaxies as they reflect the recycling of gas through star formation, galactic inflows and outflows. The environment in which a galaxy resides also plays an important role in modelling its evolution. Galaxies in dense environments such as clusters will have slightly different properties as compared to their field counterparts, because of gravitative interactions between the cluster members and hydrodynamical interactions between the hot intra-cluster medium and the interstellar medium of galaxies. In order to explore the environmental effects on gas regulation within galaxies, I have chosen to conduct a spectroscopic analysis of emission line, intermediate redshift cluster galaxies in comparison to a sample of field galaxies.

Methods. The data set on which this research is based, consists of CLASH-VLT VIMOS spectra and WFI photometry for ~ 700 intermediate and late type galaxies at $0.1 < z < 0.9$, out of which ~ 178 are members of the CLASH cluster Abell S1063 (RXJ2248-4431) with $z_{med} = 0.348$. The fluxes of $[OII] \lambda 3727$, $H\beta \lambda 4861$, $[OIII] \lambda 5007$, $H\alpha \lambda 6564$ and $[NII] \lambda 6584$ emission lines were measured allowing the derivation of (O/H) gas metallicities, star formation rates based on extinction-corrected $H\alpha$ and $[OII]$ fluxes and active galactic nuclei (AGN) contamination. The stellar masses of the galaxies were computed from the available photometric data using the code LePhare of Arnouts and Ilbert et al. (2011). In order to explore the accretion history of the RXJ2248 cluster members, a phase-space analysis was conducted. The chemical evolutionary paths of the cluster members were also investigated based on the Fundamental-Metallicity-Relation expectation of Lilly et. al (2013), in order to search for signs of star formation quenching as the galaxies travel towards the cluster centre.

Results. Our targets can be classified as blue-cloud galaxies according to the colour-magnitude diagram. Cluster and field galaxies follow the SF-sequence in the diagnostic diagrams, which allow disentangling between the ionising sources in a galaxy, with only a low number of galaxies classified as AGNs. Both field and cluster galaxies follow the "Main-Sequence" of star forming galaxies, with no substantial difference observed between the two populations. In the Mass - Metallicity (MZ) plane, both high mass field and cluster galaxies ($9.5 < \log(M/M_{\odot}) < 11$)

show comparable (O/H)s to the local SDSS mass-metallicity relation, with an offset of low mass galaxies ($8.4 < \log(M/M_{\odot}) < 9.5$) towards higher metallicities than the local MZR. We use the location of galaxies in projected phase-space to distinguish between accreted cluster galaxies, which possibly form the virialised population, and infalling galaxies, which have just been recently accreted into the cluster. Our sample of cluster galaxies is located, in projection, close to the cluster core, at radial distances lower than $2 \cdot R_{200}$. When investigating the chemical histories of the galaxies, we find the following: while both the metallicities of accreted and infalling galaxies are comparable at all masses, accreted cluster galaxies show more enhanced metallicities, by a factor of 0.07 dex, with a $\sim 1.9\sigma$ significance, than the population of field galaxies at the low mass end. The same can be said for the population of infalling cluster galaxies. The high mass galaxies are all in accordance with the expected (O/H)s from the Fundamental Metallicity Relation, while the low mass ones, especially the cluster members, deviate strongly from the model predictions, by a factor of ~ 0.4 dex, and are more in accordance with models which assume a metal enriched gas inflow. The results of this work favour the scenario in which the hot halo gas of low mass galaxies located in a dense cluster environment is stripped off due to mild ram pressure stripping, leading to an increase in the gas-phase metallicity.

Abstract German

Ziele. Gasphasenmetallizitäten bieten einen tiefen Einblick in der chemischen Entwicklung von Galaxien, da sie die Rückführung von Gas durch Sternentstehung, galaktische Zu- und Abflüsse widerspiegeln. Die Umgebung, in der sich eine Galaxie befindet, spielt auch eine wichtige Rolle bei der Modellierung ihrer Entwicklung. Galaxien, die sich in dichten Umgebungen befinden, wie z.B. Clustern, haben aufgrund der gravitativen Wechselwirkungen zwischen den Clustermitgliedern und der hydrodynamischen Wechselwirkungen zwischen dem heißen Intraclustermedium und dem interstellaren Medium von Galaxien etwas andere Eigenschaften als ihre Feldgegenstücke. Um die Auswirkungen der Umwelt auf die Gasregulierung in Galaxien zu untersuchen, habe ich mich dazu entschieden, eine spektroskopische Analyse von Emissionslinien Galaxien aus dem RXJ2248 Cluster in Vergleich zu einer Population von Feldgalaxien, durchzuführen.

Methoden. Der Datensatz, auf dem sich diese Forschung basiert, besteht aus CLASH-VLT-VIMOS-Spektren und WFI-Photometrie für ~ 700 Galaxien mit $0.1 < z < 0.9$, von denen ~ 178 Mitglieder des CLASH-Clusters Abell S1063 (RXJ2248-4431) mit $z_{med} = 0.348$ sind. Die Flüsse der Emissionslinien $[OII] \lambda 3727$, $H\beta \lambda 4861$, $[OIII] \lambda 5007$, $H\alpha \lambda 6564$ und $[NII] \lambda 6584$ wurden gemessen, und das erlaubt uns (O/H) -Gasmetallizitäten und Sternentstehungsraten basierend auf Extinktion korrigierten $H\alpha$ und $[OII]$ -Flüsse herzuleiten, und nach Kontamination mit aktiven galaktischen Kerne (AGN) zu suchen. Die Sternmassen der Galaxien wurden aus den verfügbaren photometrischen Daten mit dem Code LePhare von Arnouts und Ilbert et al. (2011) hergeleitet. Um die Akkretionsgeschichte der RXJ2248-Clustermitglieder zu untersuchen, wurde eine Phasen-Raum-Analyse durchgeführt. Die chemischen Evolutionspfade der Clustermitglieder wurden auf der Grundlage der Erwartung von Lilly et al. al (2013) analysiert, um nach Anzeichen einer Sternentstehungs-quenching zu suchen, während sich die Galaxien in Richtung Clusterzentrum bewegen.

Ergebnisse. Unsere Galaxies können gemäß dem Farben-Helligkeit-Diagramm als blaue Wolken-galaxien klassifiziert werden. Cluster- und Feldgalaxien folgen der Sternentstehungs-Sequenz in den Diagnosediagrammen, die eine Entflechtung zwischen den ionisierenden Quellen in einer

Galaxie ermöglichen, wobei nur eine geringe Anzahl von Galaxien als AGNs klassifiziert sind. Sowohl Feld- als auch Clustergalaxien folgen das "Main Sequence" der SF-Galaxien, wobei zwischen den beiden Populationen kein wesentlicher Unterschied beobachtet wird. In der Masse - Metallizität (MZ) - Ebene zeigen sowohl massenreiche Feldgalaxien als auch Clustergalaxien ($9.5 < \log(M/M_\odot) < 11$) vergleichbare (O / H) mit der lokalen SDSS-MZR, mit einem Versatz von Galaxien mit geringer Masse ($8.4 < \log(M/M_\odot) < 9.5$) zu höheren Metallizitäten als der lokalen MZR. Wir verwenden die Position von Galaxien im projizierten Phasenraum, um zwischen "akkretierte" Clustergalaxien, die möglicherweise die virialisierte Population bilden, und "einfallenden" Galaxien, die nur seit kurzem Zeit in den Cluster akkretiert wurden, zu unterscheiden. Unsere Clustergalaxien befinden sich in Projektion nahe dem Clusterkern, in radialen Abständen von weniger als $2 \cdot R_{200}$. Bei der Untersuchung der chemischen Geschichten der Galaxien finden wir Folgendes: sowohl die Metallizitäten von "akkretierte" Galaxien als auch die der "einfallenden" Galaxien sind bei allen Massen vergleichbar. Die "akkretierte" Clustergalaxien mit geringeren Massen, weisen um einen Faktor von 0.07 dex mit einem Signifikanz von 1.9σ höhere Metallizitäten als die Population von Feldgalaxien. Das Gleiche gilt für die Population von "einfallenden" Clustergalaxien. Die Galaxien mit höhere Massen stimmen alle mit den erwarteten (O/H) aus der Fundamentalen Masse-Metallizitätsbeziehung überein, während die Galaxien mit niedrigere Massen, insbesondere die Clustermitglieder, stark von den Vorhersagen des Modells abweichen, um einen Faktor von ~ 0.4 dex. Diese massenarme Galaxien sind eher in Übereinstimmung mit Modellen, die einen mit Metall angereicherten Gaszufluss annehmen. Die Ergebnisse dieser Arbeit begünstigen das Szenario, in dem das heiße Halo-Gas von Galaxien mit geringer Masse, die sich in einer dichten Clusterumgebung befinden, aufgrund eines milden Staudrucks abgelöst wird, was zu einer Erhöhung der Gasphasenmetallizität führt.

Chapter 1

Introduction

Chemical abundances of galaxies represent an important tool to study galaxy evolution, as they reflect the complex interplay between star formation, gas outflows through winds and supernovae and galactic gas inflows. A large number of studies concentrating on galaxies in the local universe have shown that there is a tight correlation between the stellar mass of a galaxy and its metallicity, the so called Mass-Metallicity-Relation (MZR): the more massive the galaxy is, the higher its (O/H) oxygen abundance will be. This relation was first observed by Rubin et. al 1984 in irregular and blue compact galaxies in the early '80s, and the luminosity was used instead of the stellar mass, as obtaining accurate masses was non-trivial at the time [22]. However, nowadays, due to large spectroscopic surveys such as SDSS, 2dF-GRS, CLASH-VLT, etc. and with help of new state-of-the-art stellar evolutionary synthesis models, one can accurately derive gas metallicities and stellar masses and explore the MZR. A secondary dependence of the gas phase metallicity at a given stellar mass was observed, that on the star formation rate (SFR). The SFR is closely linked to the amount of gas in a galaxy, which in turn is regulated by accretion of cold gas into the galaxy halo and by outflows at galactic scale. Thus, in this scenario, a relation between metallicity, SFR and stellar mass can be derived and this led to the so called "Fundamental Metallicity Relation" (FMR): galaxies with high SFR show lower (O/H) at a given stellar mass.

The mean method to derive gas metallicities is based on the analysis of nebular emission lines such as: $[OII](\lambda = 3727\text{\AA})$, $H\beta(\lambda = 4861\text{\AA})$, $[OIII](\lambda = 4959\text{\AA} \text{ and } \lambda = 5007\text{\AA})$, $H\alpha(\lambda = 6563\text{\AA})$ and $[NII](\lambda = 6584\text{\AA})$, that are accessible for most ground-based observatories at optical and NIR wavelengths. A reliable FMR requires robust metallicity calibrations, most of which rely on the flux ratios of the aforementioned emission lines. These calibrations are either computed through empirical models based on measured electron gas temperature or through theoretical methods based on photoionisation models. However, different studies have shown

that large discrepancies can occur when comparing different metallicity calibrators.

Nonetheless, not only the choice of the metallicity calibrator can influence the MZ relation. This relation is known to vary for galaxies at different redshifts and residing in different environments, with an offset towards lower metallicities for higher redshifts [8].

Observations have also shown that the internal properties such as the SFR, colour, morphology, metallicity of a galaxy residing in a dense group or cluster environment can differ from the properties of an isolated, field galaxy. A plausible mechanism which offers an explanation to the observed differences between the field and cluster populations, or to the so called morphology-density relation (early-types are the dominant population in clusters, late-types in the field), is the quenching of star formation when the galaxy is accreted into the cluster, due to the hydrodynamical interaction between the hot intracluster medium (ICM) and the interstellar medium (ISM) of the galaxy [13].

The main purpose of this master thesis is to explore the environmental effects on gas regulation within intermediate redshift field and cluster galaxies. For this objective, I was provided with a data set of ~ 700 CLASH-VLT VIMOS spectra as well as photometric data taken with the Wide Field Imager of La Silla Observatory for both RXJ2248-4431 cluster members ($z_{cluster} \sim 0.348$) and field galaxies ($0.1 < z < 0.9$). Based on the measured fluxes of strong emission lines and the computed masses from the exploited WFI imaging, the mass-metallicity- and mass-specific star formation rate - relations were derived. Furthermore, a phase-space analysis was also conducted in order to get an insight into the accretion histories of the cluster members. The chemical evolutionary paths of the cluster galaxies were also investigated to search for signs of star formation quenching triggered by starvation/strangulation as the galaxies travel through the hot ICM towards the central region of the cluster.

The outline of this work is as follows: we present in section 2 some of the fundamental physical principles in the field of extragalactic astronomy. In section 3, we give details about the data set and the measurements. We then present in section 4 the methods used to measure the emission line fluxes and to derive the stellar masses. In this section, we also discuss the sample selection. Section 5 encompasses the results: the colour-magnitude and colour mass diagrams for cluster and field galaxies, the type II AGN contamination of the sample, the measured MZR and M-sSFR relation for the two populations, the phase-space analysis and the discussion about how the cluster environment affects the chemical enrichment of the galaxies. Finally, in section 6 we summarise our conclusions.

Chapter 2

Physical principles

This chapter presents some of the main mechanisms behind the evolution of galaxies and the different means of exploring them.

2.1 Galaxy spectroscopy

Spectroscopy is a method which allows electromagnetic radiation to be split into its component wavelengths, similar to how a prism can split light. This principle was first suggested by Isaac Newton, when studying the diffractive properties of light: he postulated that white light is composed of a continuous series of colours. However, the first spectroscopic observations were carried out approximately 150 years later by Joseph von Fraunhofer, who shone the sunlight through a prism, then magnified the spectrum, and thus discovered a manifold of dark lines, which were later defined as absorption lines.

Astronomical spectroscopy began to thrive with the advance of technology, becoming one of the main methods to study celestial objects. Observers can obtain a manifold of information from a stellar spectrum, such as the chemical composition, density, mass, temperature, distance, luminosity, and relative motions using the Doppler shift. This technique can be also used to study other astronomical objects besides stars, such as nebulae, galaxies and AGNs. Spectroscopy is utilised to measure three main bands of electromagnetic radiation: radio, optical and X-ray, with different methods required to obtain the signal, depending on its frequency.

In the past, spectroscopy at optical wavelengths was carried out using prisms and photographic plates. Present day spectroscopy uses diffraction gratings in order to disperse the light, which in turn is transmitted onto CCDs. From the digital format, the 2D spectra are extracted and manoeuvred to become 1D spectra, from which one can derive different physical properties for the investigated celestial object. The calibration of the wavelength scale of a spectrum can be

done by observing the rest-frame emission of gas-discharge lamps. The flux calibration can be done by means of a standard star, for which atmospheric absorption corrections are available [4].

A galaxy spectrum can be considered to be a superposition of all the spectra of its stellar population, with its main components being the continuum emission and the spectral lines. The continuum emission, which produces a flat overall spectrum, can be defined as a combination of many Black Body spectra, which cover a large extent in temperatures. The most important feature of the continuum emission is the $4000\text{\AA}$ - Break which is produced by the absorption of high energy radiation from metals in the stellar atmospheres, being also related to the lack of hot blue stars. This means that the strength of the $4000\text{\AA}$ - Break will decrease from Ellipticals to Spirals, with Irregular galaxies showing no break.

A galaxy spectrum will show two types of spectral lines: absorption and emission lines. Spectral lines are the result of interaction between a quantum system and a single photon and are atom-specific, that's why they can be used to derive chemical abundances of celestial objects.

Absorption lines appear when a photon is absorbed by an atom, element or molecule. The photon has an energy, which is equal to the difference between two energy levels. This absorption will excite the atom, and because of this, an electron will jump into a higher energy level. Absorption lines are thus mainly caused by atoms or molecules in a star's atmosphere that absorb radiation at specific wavelengths. They can also be caused by the cold gas in the interstellar medium which extracts energy from the passing radiation. Absorption features thus point to old stellar populations, from elliptical galaxies and bulges of spiral galaxies.

Emission lines, on the other hand occur for excited atom, element or molecule, whose electrons move between energy levels, returning towards the ground state by emitting a photon. The emitted photon will have an energy, which is equal to the energy difference between the two states, due to the law of energy conservation. Emission lines are thus caused by gas being ionized and heated and then reradiated at specific allowed wavelengths. Emission features point to very hot gas, O, B type stars, and newly formed protostars and are the dominant spectral features of spiral and irregular galaxies. Important emission features are: $[OII]$ (λ 3727Å), $[OIII]$ (λ 4959Å and λ 5007Å), the Balmer series (λ 6563Å, λ 4861Å, λ 4340Å, λ 4103Å) and $[NII]$ (λ 6584Å). Figure 2.1 shows the spectral features for 4 different types of galaxies. By studying emission-line spectra one can obtain an insight into the star formation rate as well as on the nucleosynthesis processes taking place in the stellar population and on the physical conditions of the ISM. [1]

The $[OII]$ emission line, which commonly appears in the integrated optical spectra of galaxies, is

a signature of active star formation. The UV radiation from young stars can photoionize heavier elements such as neutral oxygen. The [OII] doublet is the strongest feature after $H\alpha$, but it has c.a. half its flux. The fluxes of [OII] forbidden lines can be measured in the spectra of galaxies even at higher redshifts, as this line does not fall in the region of the spectrum affected by the forest of OH sky-lines, (unlike the $H\alpha$). The [OII] forbidden line doublet is closely connected to collisional excitations and de-excitations and thus directly traces the electronic density [2].

The line emission of the hydrogen atom can be found in the ionized regions of planetary nebulae, supernova remnants and active star forming regions. The Balmer series denotes the 4 emission lines of hydrogen, which occur at optical wavelengths, $H\alpha$, $H\beta$, $H\gamma$, and $H\delta$. They are the result of the electron transitioning from a higher energy level to the energy level with quantum number 2. Young, bright protostars are usually surrounded by the clouds of gas from which they have formed, and as these stars produce energetic UV radiation, they photo-ionize the surrounding regions. The $H\alpha$ Balmer line of Hydrogen is one of the best tracers of active star formation because the luminosity of this line scales directly with the ionizing flux of the embedded star [3]. Double ionized oxygen, [OIII] originates from ionized regions not only caused by hot, young and massive stars but also by active galactic nuclei (AGNs). It is also typically found in diffuse and planetary nebulae and supernovae remnants. It is a forbidden, collisional excited line, that appears when an excited atom from a low density environment jumps from a metastable state to a lower energy level [5].

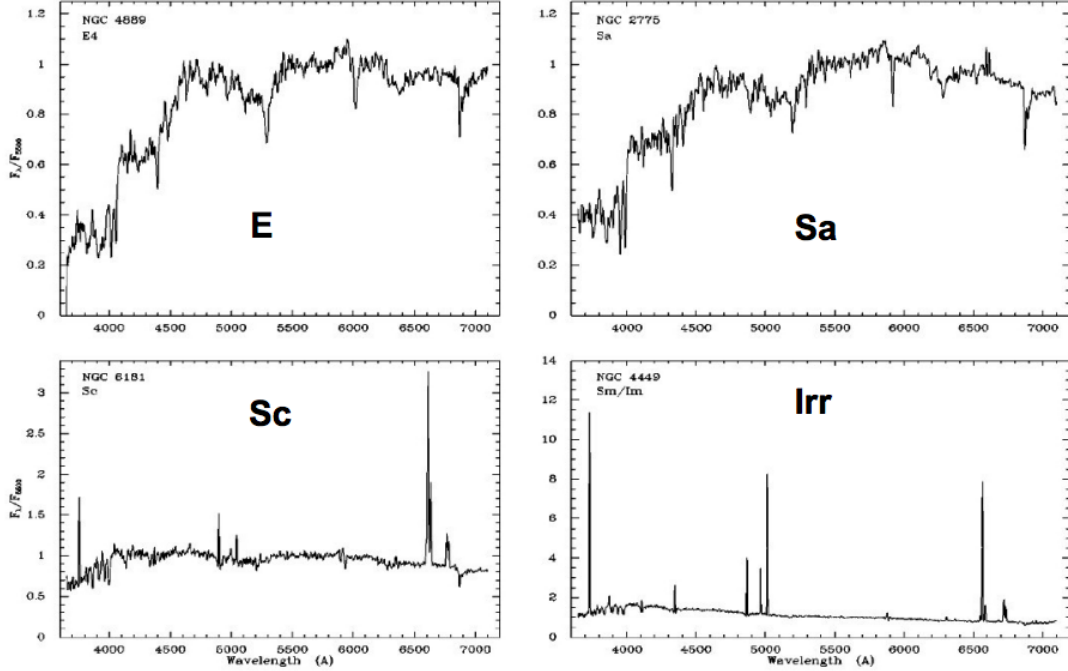
The Nitrogen forbidden double line emission [NII] traces the physical conditions and excitation of the gaseous component of galaxies. This emission line can only be excited by high energy photons of non-stellar origin, and it is thus used as a tracer for AGNs. The comparison of the line flux of [NII] to [OIII] provides a very sensitive probe of the UV field hardness as well as a sensitive indicator of the ionization state of the gas.

The strength of these emission lines reflects not only the heavy element abundance, but also the physical properties of the nebula such as the temperature, density, and ionization state and also the extinction by dust, and the depletion of metals onto dust grains [1].

2.2 Evolution of stellar populations and metallicity

As stated in the previous section, a galaxy spectrum can be considered to be a superposition of all its stellar spectra. The stellar population of a galaxy can be described by means of simple stellar populations (SSPs), which assume that all stars are coeval and share the same chemical composition, because they have formed from the same molecular cloud. Thus, the

Figure 2.1: Spectra for 4 galaxy types: Elliptical galaxy (top-left), Sa galaxy (top-right), Sc galaxy (bottom-left), Irregular galaxy (bottom-right). The strength of the 4000Å - Break decreases from early to late types. Absorption features dominate in early-types and emission features in late types.[6]



stellar component of a galaxy can be represented by a combination of SSPs - i.e. as a series of instantaneous starbursts - given any previous star formation history (SFH). The spectral evolution of an SSP can be described as follows:

- 0.001Gyrs: The spectrum of a galaxy dominated by the UV radiation produced by young, massive but short-lived stars.
- 0.01Gyrs: The UV flux will start declining and NIR flux will rise, as the most of the massive stars evolve into red supergiants and leave the main sequence.
- Between 0.1Gyr and 1Gyr : A high NIR luminosity is maintained by the AGB stars, while the UV radiation continues to drop as the turn-off mass slowly decreases on the main sequence. A strengthening of the Balmer line fluxes from the $H\alpha$ line to the Balmer continuum at 3646Å will occur at this time. This is a diagnostic for formation and a typical signature for late-B to early-F stars. As time passes, the Balmer break evolves into the 4000Å break due to a large number of metallic lines from the atmospheres of cool stars.
- Up to 4 Gyrs red giants will account for most of the NIR luminosity of a galaxy.

- Between 4-13 Gyrs a galaxy will experience only little evolution in the shape of the optical-NIR spectrum, as low-mass stars evolve within a narrow temperature range from the main sequence to the end of the AGB [7].

Metallicities are tightly coupled to the evolution of galaxies, as they reflect the interplay between gas accretion, star formation and galactic winds, making them one of the most fundamental properties of galaxies. Large aperture telescopes as well as sensitive spectrographs, which perform rest-frame optical emission-line spectroscopy, allow us to measure the chemical properties of the ionized gas in close vicinity of SF regions within galaxies, by applying the same nebular analysis techniques used in local HII regions. The chemical composition of a galaxy will offer an insight into its SFH, as it traces the accretion of metal-poor gas from the IGM, which fuels star formation. It also gives an insight into enrichment of the ISM/IGM because, as stars terminate their lives, they contribute metals to the ISM via supernovae and stellar winds and they also power galactic-scale outflows of metal-enriched gas. The gas-phase metallicity of a galaxy represents the sum of the mass fractions of all the elements which are heavier than helium, and as oxygen has the highest cosmic abundance, making up more than half of the total mass fractions of metals in the Sun, the oxygen abundance is often used as a synonym to the metallicity. The abundance of oxygen is then defined as the ratio of its number density to that of hydrogen.

Gas phase metallicities can be derived by a manifold of techniques using the relative strengths of strong emission lines, more details to these empirical methods are given in section 5.4.1.

Chemical evolution modelling represents a fundamental tool in astronomy, which allows reckoning how a system was formed, by constraining the history of the SFR or of various gas cycles. Such a model is described in the section that follows.

2.3 The Fundamental Metallicity Relation and the Bathtub model

The Bathtub model of Lilly et. al 2013 represents a very simple physical model of galaxies in which the star formation is instantaneously governed by the amount of gas in the galaxy's reservoir, and by gas inflows and outflows. Within this simple model, the SFR scales directly with the mass loss. This chemical evolution model connects different physical aspects of the evolving galaxy population: the cosmic evolution of the specific star-formation rate together with the growth of halos, the evolution of gas-phase metallicities across the galaxy over cosmic time, and the ratio of the stellar to dark matter halo mass. As the evolution of the SFR and the gas-phase metallicity of galaxies are the main purposes of this work, this section will describe these two physical aspects in more detail.

A manifold of observations have shown, that out to $z \sim 2$ there exists a main sequence (MS) of star forming galaxies, in which the SFR is closely correlated with the stellar mass of a galaxy. If galaxies show a scatter c.a 0.3 dex around this mean relation, that means that they are MS SF-galaxies. 1%2% of SF galaxies lie above the MS making them starburst galaxies, whereas a substantial population will lie below the MS, meaning that these galaxies make up the "quenched", passive population. Most stars, therefore, form in main-sequence galaxies, these systems representing the main subject of this work. The MS has a characteristic sSFR that declines weakly with the stellar mass as:

$$sSFR \propto m_{star}^{\beta} \text{ with } \beta \sim -0.24 \quad (2.1)$$

Observations also demonstrate that the sSFR on the MS strongly evolves with redshift as:

$$sSFR \propto (1+z)^3 \quad (2.2)$$

For a given mass, the SFR has been decreasing at a steady rate by a factor of ~ 20 from $z = 2$ to $z = 0$ [8].

Observations have also shown, that there is a strong correlation between the stellar mass of a galaxy and its gas-phase metallicity. Tremonti et al. 2004 have illustrated this mass-metallicity relation (MZR) very well based on the data from Sloan Digital Sky Survey: the more massive the galaxy is, the higher its (O/H) oxygen abundance will be. The origin of this relation was argued as follows: either galactic winds can remove metals more efficiently from low mass galaxies, which have shallower potential wells, or low-mass galaxies convert their gas reservoirs into stars over longer timescales than galaxies of higher mass meaning that lower-mass galaxies should have larger gas-to-mass ratios and that they are less metal enriched. Another explanation for the origin of the MZR is given by flatter IMF with a higher fraction of massive stars in more massive galaxies. There is also good evidence that this MZ relation evolves with redshift: for a given mass, gas-phase metallicities are higher at lower redshifts. Based on the extensive SDSS data, it has also been claimed that gas phase metallicities correlate with other galactic parameters as well, such as the SFR. Observations have demonstrated an anti-correlation of oxygen abundances with SFR, especially at low stellar masses, meaning that at a given mass, galaxies with high SFR will show lower (O/H). The correlation between stellar mass, sSFR and (O/H) was then defined as the fundamental metallicity relation (FMR) [9].

The gas-regulated galaxy model developed by Lilly et. al 2013 is built around the close coupling of baryons to dark matter and assumes that the gas, which is mixed with dark matter flows from the surrounding IGM into the halo of the galaxy. Some fraction f_{gal} of this inflowing material will enter the galaxy system and will add up to its gaseous reservoir at a rate Φ . The mass of this

gas reservoir is the one parameter regulating the SFR. As stars terminate their lives, metals are returned to this internal reservoir. Of course, some material may be expelled from the reservoir back out to the halo, or even out of the system, in form of a galactic wind. This process is described by the mass loss rate ψ . Figure 2.2 gives an illustration of this simple gas-regulated model.

This model assumes that changes in m_{gas} must be associated with an inflow into or out of the reservoir. The gas which falls into the galaxy system from the surroundings has some prior chemical abundance Z_0 , and the gas flowing back out will be chemically enriched with a similar composition to that of the gas reservoir. The inflow rate Φ can be expressed as:

$$\Phi = (1 - R + \lambda) \cdot SFR + \frac{dm_{gas}}{dt} \quad (2.3)$$

where R stands for the fraction mass returned to ISM and λ for the mass-loading factor. In this model, the SFR is proportional to the amount of gas:

$$SFR = \varepsilon \cdot m_{gas} \quad (2.4)$$

where ε stands for the star forming efficiency. Stars continuously form out of the reservoir at a rate proportional to m_{gas} , characterised by the SF efficiency ε :

$$\varepsilon = \frac{1}{\tau_{gas}} \quad (2.5)$$

where τ represents the gas consumption timescale. In a given interval of time, some of the gas in the reservoir forms stars, and a fraction $(1-R)$ steadily builds up a population of long-lived stars. As stars terminate their evolution, some fraction of the stellar mass is returned to the reservoir, along with the newly produced metals. However, some of the metal enriched gas will be expelled out of the system at a rate ψ :

$$\Psi = \lambda \cdot SFR \quad (2.6)$$

where λ represents the mass-loading factor, which may vary with the mass of the galaxy because of the depth of the potential well, or other factors.

For an ideal self-regulator system, the parameters describing the SF efficiency and the mass loading of the wind should be constant. However, it is expected that for real systems ε and λ will both depend on galactic mass and on the epoch, and will change for a given galaxy as it evolves and increases in mass.

The gas phase metallicity in the gas-regulated model is set by the constant or slowly varying parameters of the regulator: ε , λ and sSFR. The gas metallicity is mainly independent of the galaxies past evolutionary path, as gas is continuously flowing through the system since the gas

consumption timescale τ_{gas} is short. If the gas which flows into the halo has a metallicity Z_0 , then the change in the mass of metals within the gas reservoir will be expressed through the yield. The yield is defined as the ratio between the mass of metals ejected into the ISM and the mass of metals that is locked up into long-lived stars, i.e. $(1-R)$ times the mass of stars formed. The solution to the a steady-state gas-regulated reservoir will be then given by the following equation:

$$Z_{eq} = Z_0 + \frac{y \cdot (1 - R) \cdot SFR}{\Phi} \quad (2.7)$$

with Z_{eq} being the equilibrium value for the metallicity. Based on equation 2.7, one can notice that a suppressed Φ or an elevated Z_0 can enhance the gas phase metallicity of galaxies.

The gas-regulated model produces an implicit dependence of the gas-phase metallicity and the SFR. The metallicity of this simple model also shows a dependence on the mass of the galaxy, especially if ε and λ are varying parameters. Thus, the fundamental metallicity relation $z(m_{star}, SFR)$ is a natural outcome of the simple operation of the regulator model. It is also expected that the dependence of the SFR on the massmetallicity relation would be stronger for lower mass galaxies if the star formation efficiency was also lower at lower galactic masses. Furthermore, the FMR is also epoch-invariant in the bathtub model, as long as ε and λ do not change with redshift.

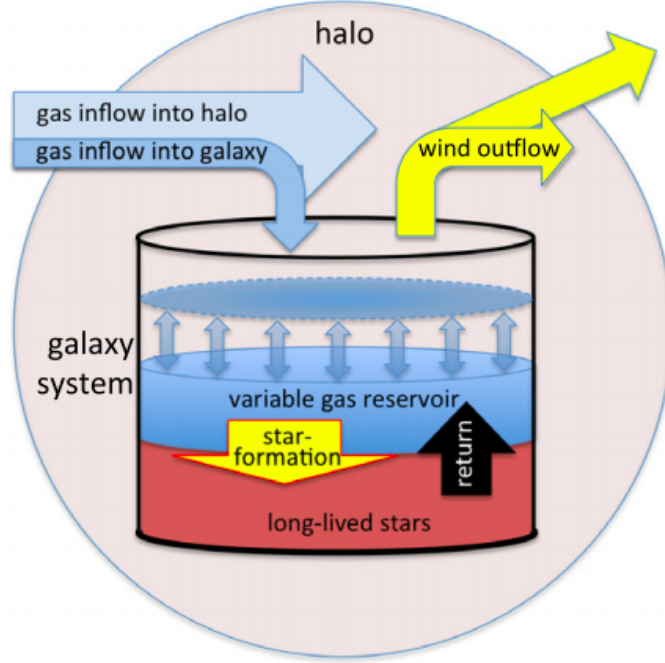
This gas-regulated model can be therefore used as a basic description for the galaxy population over a wide range of epochs and it also shows that the chemical abundances in galaxies are directly linked to the operation of this regulatory system [8].

2.4 Impact of environment on galaxy evolution

The environment in which a galaxy resides can have a great impact on its evolution. We know, according to Geller and Huchra et al. 1989, that the density of galaxies in the local universe is not constant, but it spans from up to $\sim 1000\rho_0$ in compact groups to $\sim 100\rho_0$ in the cores of rich clusters down to $\sim 5\rho_0$ in filaments and superclusters and $\sim 0.2\rho_0$ in voids, where ρ_0 stands for the average field density. Galaxies which reside in dense environments will have slightly different internal properties as compared to isolated galaxies from the field [10].

Observations have shown that the local density and the morphological type of galaxies are actually not independent quantities, leading to the so-called phenomena of morphological segregation, which was first proposed by Dressler et al. 1980. Early-type galaxies dominate in clusters, particularly cluster centres, while late-type galaxies dominate in the field [11]. Dressler et al. 1997 also found that the fraction of lenticular galaxies in clusters has increased by a

Figure 2.2: Illustration of the gas-regulated model [8].



significant factor between $z = 0.5$ and today, while the fraction of star-forming spiral galaxies experience a decrease. This phenomenon is considered to be the clearest observational signature that the processes that govern the formation and the evolution of galaxies have an environmental dependence. A manifold of studies has tried to explain the predominance of early type galaxies in clusters as the result of physical processes that quench star formation and eventually reshape the morphology of the galaxy [12]. Galaxies which reside in clusters will be shaped by two types of interactions: gravitative interactions between the cluster members and hydrodynamical interactions between the hot ICM and the ISM. Collisions and/or close encounters between cluster members can have a strong effect on their morphology and star formation rates. Gravitative galaxy interactions in clusters will lead to the following phenomena:

- *Dynamical friction*
- *Mergers*
- *Galactic cannibalism*
- *Harassment*

Dynamical friction, which is the loss of kinetic energy and momentum of the moving galaxies through gravitational interactions with surrounding environment, has two consequences: the most massive galaxy sinks to the centre of the cluster and can grow there via mergers with other

galaxies. The debris from the mergers can lead to the formation of extensive halos.

Mergers are however pretty rare in cluster environments due to the high relative velocities of the cluster members, with exception of the brightest cluster galaxy (BSG), which is taught to be a merger remnant. This BSG, which in some extreme cases is the central dominant galaxy (cD), is taught to have formed through galactic cannibalism. Mergers occur most likely at group densities, and this pre-processing of galaxies in groups will influence the cluster galaxy population. A manifold of simulations has shown that major mergers between disk galaxies produce as remnant elliptical galaxies and that wet minor mergers can transform spirals to lenticular galaxies. The tidal forces produced during these mergers lead to a gas accumulation towards the galaxy centre, and this fuels a central starburst (and sometimes AGN ignition), which leads to the ejection of a large fraction of material. Nevertheless, for eg. Moore et al. (1996) has showed that galaxy harassment, i.e the cumulative effect of many weak high velocity interactions, can have a strong influence on cluster galaxies. Harassment is the phenomena in which repeated galaxy-galaxy encounters together with tidal forces from the overall cluster gravitational potential can strip stars and gas from a galaxy and kinematically heat the remnant. Hydrodynamical galaxy interaction with the hot intra-cluster medium will lead to:

- *Ram-pressure stripping*
- *Starvation/Strangulation*
- *Viscous stripping*
- *Thermal evaporation*

The gas inside of a galaxy moving through a galaxy cluster will feel pressure by the ICM. When the ram pressure is greater than the binding force within the galaxy, the cold gas will be stripped from its ISM. This is the phenomena of ram-pressure stripping and it will lead to a gradual decrease in the star formation activity of a galaxy. Observations have shown that this mechanism is likely to be more effective at high ICM densities, so in the central region of clusters.

Mild ram pressure stripping also known as starvation/ strangulation is the mechanism which leads to the removal of the diffuse hot gas reservoir that is confined in the galaxy halo. The stripping of the hot halo gas occurs easier as it is not as strongly gravitationally bound as the cold disk gas. Starvation thus leaves the cold disk gas intact, meaning that star formation can still occur until the gas, which cannot be replenished by gas infall from halo, is consumed. It is worth mentioning that while stripping gas from disks induces a truncation of star formation activity on a short timescale of $\sim 10^7 yrs$, strangulation is expected to affect the star formation history of a galaxy on timescales larger than 1 Gyr.

The outer parts of the ISM of a galaxy moving through the hot ICM will also experience a viscosity momentum transfer which can lead to some part of the gas being stripped off. This phenomenon is known as viscous stripping and can affect the SFR of a galaxy. It is expected that viscous stripping is more effective at high ICM densities.

Another mechanism which affects the gaseous reservoir of cluster galaxies is the thermal evaporation. If the temperature of the ICM is high as compared to the galaxy velocity dispersion, then at the interface between the hot ICM and the cold ISM the temperature of the ISM will start rising and this will lead to gas evaporation and it can not be retained by the gravitational potential of the galaxy anymore [13].

All the aforementioned mechanisms have an impact on the physical properties of galaxies, such as their morphology, gas-phase metallicities and SFRs. Observations have shown that the specific star formation rates are slightly lower for cluster galaxies than for the field population [14]. It is also known that these cluster specific interactions are more likely to affect low mass galaxies, meaning that the suppression of sSFRs is stronger for low-mass cluster galaxies. Gas-phase metallicities are also affected by the hydrodynamical interactions of the ISM with the ICM.

Maier and Ziegler et al. 2016 studied the environmental effects on gas regulation within galaxies of another CLASH cluster, MACSJ0416, and found that mechanisms such as strangulation can lead to enhanced metallicities, especially in low mass cluster galaxies [15]. Maier and Ziegler et al. 2018 tested these results using a larger sample of LoCuSS cluster galaxies, and found again, that accreted cluster members show more enhanced metallicities than infalling and field galaxies [63]. More details to the impact of these cluster specific interactions on the cluster members are given in section 5.8.5.

Chapter 3

The data

The data set consists of both CLASH-VLT field and RXJ2248-4431 cluster galaxies. In this chapter I summarise the main goals of the CLASH-VLT survey, I present some key properties of the RXJ2248-4431 cluster as well as some details regarding the observations.

3.1 CLASH-VLT survey

CLASH is the acronym for Cluster Lensing and Supernova survey with Hubble. The project was approved in 2011 in order to provide measurements of the mass distribution of massive clusters and to carry out a systematic search for gravitationally lensed galaxies at high redshifts, using the Advanced Camera for Surveys and Wide Field Camera 3 instruments of Hubble Space Telescope. It is 1 of 3 Multi-Cycle Treasury Programs with Hubble, having 524 orbits allocated in order to obtain panchromatic 16-filter imaging for 25 galaxy clusters.

The CLASH-VLT survey, which is based on the CLASH-HST panchromatic imaging project, is the follow-up spectroscopic campaign on 13 CLASH clusters accessible from the Very Large Telescope (VLT), at Cerro Paranal in the Atacama Desert of Chile. One of these CLASH clusters is RXJ2248-4431, the cluster on which this work is based. The survey had 225 hours allocated for observations, with 200 hours of multi-object spectroscopy and 25 hours of pre-imaging, primarily using the VIMOS spectrographs' low-resolution LR-blue grism and the middle-resolution MR-grism, when magnified sources at high redshifts were present. Additional observations for this programme are archival imaging data provided by two other instruments, the ESO Wide Field Imager (WFI) of the 2.2-m MPG telescope of La Silla Observatory for the southernmost target RXJ2248 and Subaru Suprime-Cam of the Subaru telescope at Mauna Kea Observatory, Hawaii for the rest of the clusters.

The scientific goals of CLASH-VLT can be divided into three categories:

- Spectroscopic confirmation of ~ 500 members per cluster and dynamical analysis out to $2 \times R_{200}$.
- Redshift estimation for ~ 200 lensed galaxies in the cores of the clusters, as well as for magnified galaxies at high redshifts out to $z \sim 7$.
- Providing a data set that will enable the investigation of distinct galaxy populations residing in different environments with a full set of multi-wavelength data.[16]

3.2 VIMOS

VIMOS stands for Visible Multi Object Spectrograph and was an imaging spectrograph mounted at the Nasmyth focus B of Unit 3 of VLT at the Paranal Observatory in Chile. At the time, it was the instrument with the highest multiplexing capabilities available. The spectrograph is split into 4 identical optical channels, called quadrants. Each of these 4 VIMOS quadrants is a classical focal reducer imaging spectrograph with a field of view of $7' \times 8'$, separated by a gap of $2'$. Each channel is equipped with 6 grisms, providing a spectral resolution range from 200-2500. The grisms are the following: LR blue, LR red, MR, HR blue, HR orange and HR red, where LR, MR and HR stand for low, medium and high resolution, respectively. The wavelength range covered in the spectroscopic modes goes from 360 to 1000 nm, depending on the used grisms. VIMOS operates in three different modes :

1. Imaging
2. Multi-object (MOS) low to high resolution spectroscopy
3. Integral field unit

The relevant mode for this work is the multi-object spectroscopy, as this mode enables the possibility to place multiple slits on the field of view and simultaneously obtain up to 1000 spectra during one exposure. MOS is carried out using one mask per quadrant, and the maximum number of slits per mask can vary from 40 at $R=2500$ to 150-200 at $R=200$.

The VIMOS multiplexing capabilities and field of view, which covers approximately 10 Mpc at the redshift 0.4, are very well suited for the CLASH-VLT project. For each CLASH cluster, 8-12 VIMOS pointings were used, spanning an area of 1520 square arcminutes. One quadrant was kept locked onto the core of the cluster in order to increase the total exposure time for the faint lensed sources.

3.3 CLASH RXJ2248-4431 cluster

As stated earlier, the main focus of this work is the CLASH RXJ2248-4431 galaxy cluster, also known as Abell S1063, first identified by Abell et al. (1989). RXJ2248 is one of the 25 CLASH and one of the 13 CLASH-VLT clusters. The astronomical object was also observed during the HST Frontier Fields project, using the Wide Field Camera 3 (WFC3) infrared detector, and the visible-light Advanced Camera for Surveys (ACS).

The galaxy cluster has the following equatorial coordinates : RA = 22:48:44.29 & DEC = -44:31:48.4. The system has a median redshift of $z \sim 0.348$, and its members show large velocity dispersions of 1840 km s^{-1} . Chandra X-ray observations of RXJ2248 revealed a very high X-ray luminosity as well as a very hot intracluster gas with a temperature of up to $\sim 14.3 \text{ keV}$. Both the high velocity dispersion and X-ray temperature suggest that Abell S1063 is a very massive cluster with an estimated mass, according to Gmez, P. L. et al. 2012, of $M_{200} > 2.5 * 10^{15} M_{\odot}$ that probably formed through a merger event. The total mass distribution has been studied using different probes such as strong and weak lensing analysis and X-ray emission, with a general good agreement between the different techniques. The merger scenario is supported by a non-Gaussian galaxy velocity distribution, by a small offset between the galaxy density and the peak of the X-ray emission. The RXJ2248 cluster has over 1000 spectroscopically confirmed cluster members [17].

3.3.1 CLASH-VLT VIMOS spectra

The observations for the RXJ2248 cluster were carried out between June 2013 and May 2014. The data set consists of ~ 700 CLASH-VLT VIMOS already reduced galaxy spectra, both in the field around RXJ2248 and cluster members. The spectra were obtained with the VIMOS spectrograph, with a total of 16 masks observed, 12 with the LR grism and 4 with the MR grism. The VIMOS slit-masks were designed into sets of four pointings, with one of the quadrants centred on the cluster core. The spectra that I use were registered with the 4 MR masks, with a resolution of $R=580$, containing ~ 200 slits per quadrant. The covered wavelength range is $4800\text{-}10000\text{\AA}$, thereby including emission lines from $[OII]\lambda 3727$ to $[NII]\lambda 6584$ for $z < 0.5$ galaxies, and $[OII]\lambda 3727$ to $[OIII]\lambda 5007$ for $0.5 < z < 0.9$. The observations were carried out at a wavelength domain contaminated by only a few strong OH sky lines. A summary of the CLASH RXJ2248 observations with VIMOS is presented in Table 3.1. The data reduction of ~ 700 galaxy spectra, as well as the redshift determination was done with VIPGI, the VIMOS Interactive Pipeline and Graphical Interface, by the CLASH-VLT team. The field galaxies span

Figure 3.1: Hubble image of galaxy cluster RXJ2248-443. The image is a composite of separate exposures acquired by Hubbles Advanced Camera for Surveys (ACS) and Wide Field Camera 3 (WFC3) instruments. Seven filters were used in order to sample many wavelengths. The colours result from assigning a different colour to each monochromatic image associated with each individual filter. Gravitational arcs can be clearly seen. [18]



a redshift range of $0.01 < z < 0.9$ with a few high-redshift objects up to $z=6$, while the RXJ2248 cluster has a redshift of $z \sim 0.348$, according to the literature. Further details regarding the data selection will be given in sections 4.3.1 and 4.3.2.

3.4 WFI

WFI is the acronym for Wide Field Imager, an instrument mounted at the Cassegrain focus of the 2.2-m MPG/ESO telescope at La Silla Observatory. WFI is a focal reducer-type camera, with a field of view of $34' \times 33'$ and a Nyquist sampled by $0.238''$. The camera is built around eight CCDs and offers high sensitivity from 350 nm to the near IR, with more than 40 filters simultaneously available. Many of the filters are specifically selected to support the determination of photometric redshifts of distant astronomical objects, such as quasars. The filters include the U,B,V,R and SDSS g,r,i,z filters which are standardly available for all programs. In terms of its sensitivity, WFI goes to 24th magnitude [21].

3.4.1 Archival imaging data with WFI

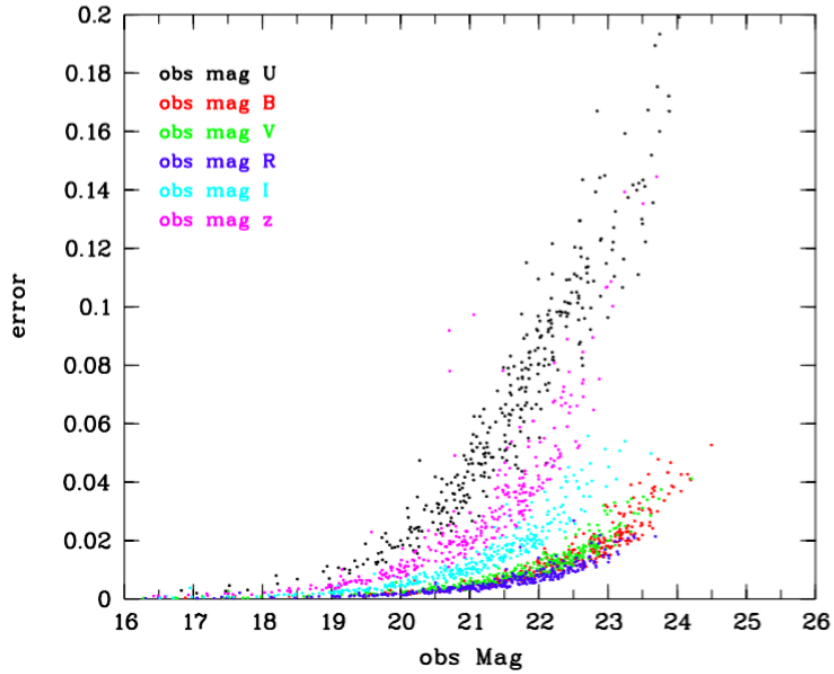
Additional key observations for the CLASH cluster RXJ2248 are archival imaging data taken with the ESO Wide Field Imager (WFI). I use a catalog with the observed UBVRIZ magnitudes

Table 3.1: Summary of CLASH RXJ2248 observations with VIMOS[20].

Mask ID	Observation date	Exposure time (s)
MOS_R22248_MR_1_M1	Jul 2013	3 x 1200
MOS_R22248_MR_2_M1	Jul 2013	3 x 1200
MOS_R22248_MR_3_M1	Jul 2013	3 x 1200
MOS_R22248_MR_4_M1	Jul 2013	3 x 1200

together with the error for each filter for 636 field and cluster galaxies, see figure 3.2. The photometric data was already corrected for galactic extinction according to Schlafly and Finkbeiner et al. 2011.

Figure 3.2: Observed magnitude versus error for the ~ 636 investigated galaxies, for which photometric data is available. The colour code stands for the observed magnitudes in the different WIF filters.



Chapter 4

Methods

In this chapter, we describe the methods used to measure the fluxes of the emission lines (ELs) $[OII] \lambda 3727$, $H\beta \lambda 4861$, $[OIII] \lambda 5007$, $H\alpha \lambda 6564$, and $[NII] \lambda 6584$ that are relevant for the BPT diagnostic, and for the computation of gas-phase metallicities and SFRs. We also discuss the procedure used in order to compute the stellar masses for the investigated galaxies, based on the photometric data. The criteria for the sample selection and the final data set are also presented in this chapter.

4.1 Measurement of the emission line fluxes

The ELs $[OII] \lambda 3727$, $H\beta \lambda 4861$, $[OIII] \lambda 5007$, $H\alpha \lambda 6564$, and $[NII] \lambda 6584$ are relevant for this work, as the computation of the BPT diagnostic diagram, as well as the derivation of oxygen abundances and SFRs rely on the measured fluxes of these lines. The fluxes of these spectral lines, as well as their equivalent widths were measured with help of three softwares: VIPGI, *splot* in IRAF, and FADO.

4.1.1 VIPGI

VIPGI stands for VIMOS Interactive Pipeline and Graphical Interface, and is a specially designed software for reducing astronomical data obtained with the VIMOS spectrograph. The software package is publicly available for all astronomers since June 2005, and it was coded using the Python and C language. The functions of VIPGI can be divided into two main units: the data reductions recipes and the graphical interface unit. The core of the VIPGI pipeline is composed of a set of routines performing the data reduction, developed in collaboration with the ESO Data Management Division. The data reduction recipes include wavelength calibration, production of master -bias,-flat and -lamp files, the reduction of each individual science file

and finally the composition of more science files to one master file. The data-reduction scheme implemented by VIPGI broadly follows the one implemented by the IRAF package. As VIMOS is split into 4 quadrants that correspond to four physically distinct cameras within the instrument, all calibration and science data reduction procedures are carried out on each quadrant data independently.

However, of interest for this thesis is the graphical interface unit of VIPGI, as the data provided for this work was already reduced with this software package. The graphical interface offers a multitude of possibilities to analyse and organise the data. The main function of the graphical interface, that was also used for this thesis, is the Spectra Plotting and Analysis tool. These tools allow the user to plot each extracted one-dimensional spectra, together with the corresponding two-dimensional spectra and the one-dimensional sky spectra. It is also possible to zoom in and out of all 3 spectra, to edit the one-dimensional spectrum, to smooth it with a square window function, to fit the position of spectral lines, and to measure the signal to noise over a selected wavelength interval. The tool also offers the possibility to get redshift estimates by marking the position of a set of prominent emission or absorption lines, and by using a function that will display a list of possible redshifts based on a list of known spectral lines in the galaxy spectra. The first task for which VIPGI was used within this work, was in order to check the accuracy of the wavelength calibration. This was done by visually inspecting the 2D spectrum with *skycat* and by using the *Show Lambda Calibration* tool. The latter is a very useful tool, as it offers many options to investigate the quality of the λ -calibration. The user can analyse each line or each slit individually. The first option shows the precision of one certain line in all slits, whereas the second one shows the precision of all lines for a certain slit. Individual lines that seem off can be selected and removed. The precision is measured in rms-values, where the mean rms of all slits should be around 1/7 of the pixel size. The MR grism has a dispersion of $2.5 \text{ \AA}/px$, meaning that the mean rms should be around $\sim 0.36 \text{ \AA}$. Besides individual lines and slits, the Show Lambda Calibration tool can display a histogram with the rms values for all slits, and thus the user can see which slits are rather bad and then critically investigate them again. In the case of the ~ 700 galaxy spectra that I was provided with, there were minor problems with the wavelength calibration for MR mask number 4, quadrant 1, slits 11-14 and MR mask number 1, quadrant 2, slits 59 and 60. Due to the fact that these spectra corresponded to field galaxies, I have chosen to exclude these objects from my work.

VIPGI also comes in handy when visually inspecting the spectra, in order to check whether the spectral features that are present in the 1D spectrum are real or just artefacts due to OH sky lines. For this purpose, I have used the VIPGI tool *Show Slit Summary*, designed to plot and

analyse MOS spectra. This command offers the possibility to plot each 1D galaxy spectrum of a MOS mask, together with the corresponding 2D spectrum and the sky 1D spectrum, see figure 4.1. The latter two spectra are very useful in order to determine if the investigated spectral lines are real. The 2D spectrum of a galaxy contains the spatial information on the y-axis and the wavelength information on the x-axis whereas the 1D spectrum contains the flux information on the y-axis and the wavelength information on the x-axis. Strong emission lines will appear as bright spots on the continuum emission, seen as a bright horizontal line, whereas sky lines will appear as dark line-like features in the 2D spectrum [23].

The airglow, a faint emission of light caused by the planetary atmosphere, should be carefully taken into account when analysing galaxy spectra. This night-sky emission imprints a faint continuum and rich line spectrum on every spectroscopic observation. This phenomenon is caused by a multitude of processes in the upper atmosphere of Earth, such as the recombination of photoionised atoms, luminescence caused by cosmic rays interacting with the upper atmosphere, and chemiluminescence that is caused by oxygen and nitrogen reacting with hydroxyl ions. At optical-wavelengths, there is only a low number of sky-lines contaminating the spectrum, however as one goes to IR-wavelengths, the number of lines of the OH (vibration-rotation) bands strongly increases [24].

Taking all of this into account, an emission feature in the 1D galaxy spectra can be considered as being real when it does not overlap a sky line and when it corresponds to a bright spot in the 2D spectrum.

VIPGI also offers an option to show the location of each spectral feature if the redshift of the galaxies is known. As the VIMOS spectra that I was provided with were not de-redshifted, I have used VIPGI for visualising the location of the emission lines, and the *splot* IRAF package to measure the line fluxes.

4.1.2 *splot* in IRAF

IRAF stands for Image Reduction and Analysis Facility and is a general purpose software system specially designed for the reduction and analysis of astronomical data. IRAF commands are organised into multiple package structures, ranging from tools that allow data reduction, calibration of the fluxes, determination of positions of astronomical objects within an image, compensation for sensitivity variations between detector pixels, combination of multiple images or measurement of fluxes of absorption or emission lines in a spectrum.

The package used within this work is *splot*, contained in the *specred* package. This tool provides an interactive facility to plot and analyse spectra. The plots are displayed on the graphics

by exploring rather extreme possibilities. The equivalent widths for the $H\alpha$ and $H\beta$ lines were also measured following the same procedure as above. Figure 4.2 shows the fitting procedure with `splot` in IRAF for the $H\alpha$ emission line.

Quality flags were assigned to all the ~ 700 investigated galaxy spectra. If a quality flag $f=1$ was attributed to a spectrum, then all the emission line fluxes ($[\text{O II}]$, $H\beta$, $[\text{O III}]$, $H\alpha$, $[\text{N II}]$) could be measured. If a spectrum is described by a quality flag $f=2$, then the measurement of one emission line flux was problematic: either the emission line was very weak, with a very low signal to noise (S/N) or the respective line overlapped a sky-line, meaning that it was not real. A quality flag $f=3$ denotes the fact that two or more emission line fluxes could not be measured. Most galaxies described by a quality flag $f=3$ are actually early-types showing few/no emission lines whatsoever.

When compared to theoretical values, the observed ratios of $\frac{H\alpha}{H\beta}$ constrain the degree to which the stellar atmospheric absorption lines reduce the measured Balmer emission, as well as the amount of reddening induced by dust. Spectra with high signal to noise are required for this. However, global galaxy spectra, especially at higher redshift, will seldom have the wavelength coverage and signal to noise necessary to decouple these effects. In the absence of very high-quality Balmer line measurements, statistical correction should be applied to the measured strength of the Balmer emission lines, particularly the $H\beta$ emission line. Kobulnicky et al. 1999 assumed an average underlying stellar absorption in $H\beta$ of $3 \pm 2 \text{ \AA}$ and corrected the equivalent width of the spectral line by this amount, thereby increasing the $H\beta$ line flux. This correction is needed mainly when the emission line is weak compared to the continuum. Such corrections of the $H\beta$ emission line flux are often used in literature for data at similar redshifts and with similar spectral resolution as the one used within this work.

The correction for $H\beta$ absorption is given by the following equation [26]:

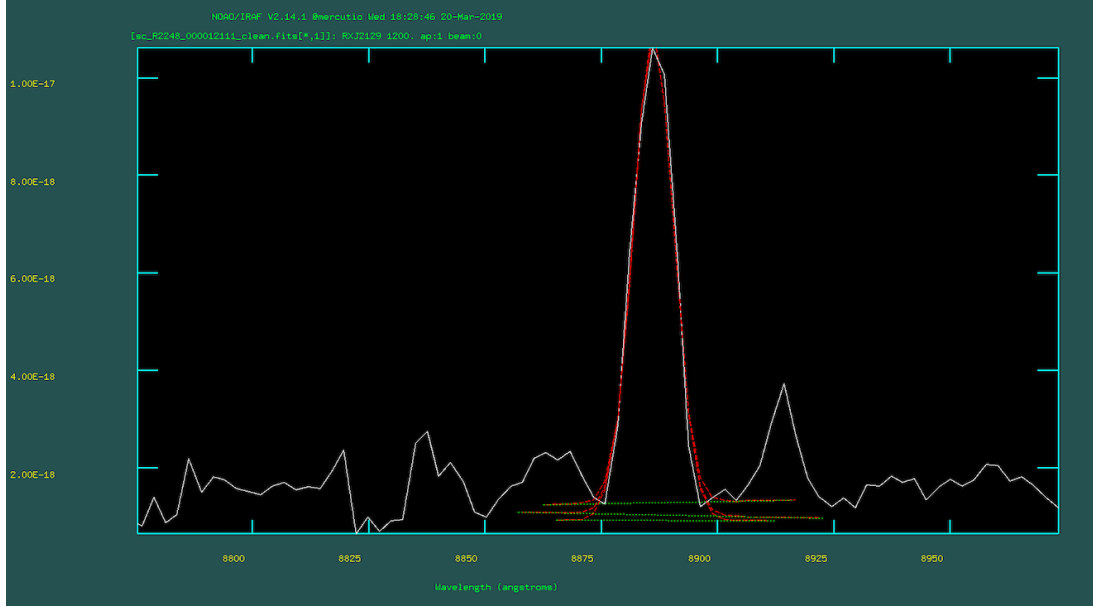
$$H\beta_{corrected} = H\beta + 3 \cdot H\beta / EW_{H\beta} \quad (4.1)$$

In order to test whether the measured fluxes with `splot` in IRAF are accurate, an additional code, FADO, which performs population spectral synthesis was used on the VIMOS spectra.

4.1.3 FADO

FADO is the acronym for Fitting Analysis using Differential Evolution Optimisation and is a tool specially designed to perform population spectral synthesis (pss) in order to derive different physical parameters from a galaxy spectrum. Population spectral synthesis is a technique which decomposes an observed galaxy spectrum in terms of a superposition of simple stellar populations

Figure 4.2: This figure shows the fitting-procedure for the $H\alpha$ emission line in splot in IRAF. The software prints out the values for the centre, continuum at the centre, core intensity, integrated flux, equivalent width, and FWHMs. Three Gaussian fits were applied to each line in order to increase the accuracy of the flux measurements.



of various ages and metallicities. FADO is the first pss code which uses genetic differential evolution optimisation, resulting in an improved computational efficiency. The software also incorporates within a single code the entire chain of modelling, pre- and post-processing together with the storage and graphical description of the output from pss. The main goal of FADO is to derive the chemical enrichment and the star-formation history of galaxies based on 2 elements in spectral fitting models:

- self-consistency between the best-fitting star formation history and the nebular emission of the galaxy
- artificial intelligence algorithms and genetic optimization

FADO is more advantageous over other existing pss codes because :

- It computes and incorporates the contribution of the nebular continuum to the best-fitting SED.
- It identifies the ages, metallicities and mass fractions of individual, simple stellar populations that best reproduce the nebular characteristics of the investigated galaxy.
- Using artificial intelligence, it automatically characterises the input spectrum in order to optimise the SSP library and fitting strategy.

- It computes and stores the errors of the computed parameters.
- It computes the electron temperature and density of the ionised gas.
- It determines the intrinsic extinction in the nebular and stellar component.
- It offers high computational efficiency and stability.

The main components of FADO can be divided into three parts: pre-processing of spectral data, spectral synthesis and computation and storage of the model output. The pre-processing mode includes: importing of the spectra, initial redshift determination, auto-determination of the error spectrum, preliminary spectroscopic classification, initial guess for the fitting strategy and the optimisation of the SSP library through artificial intelligence. The second module in FADO handles the fitting procedure of the spectra and includes the following steps: measurement of emission line fluxes and equivalent widths, determination of the physical conditions in the gas, decision-tree based choice for the fitting strategy and the convergence schemes, derivation and evolution of several evolutionary threads, computation of the Lyman continuum, derivation of nebular continuum and of the predicted Balmer-line luminosities and estimation of uncertainties. The third module of FADO encompasses the final measurement of emission-line fluxes, the computation of secondary evolutionary quantities, exportation of the relevant model output and finally exportation of the graphic output. Figure 4.3 gives a schematic view of the strategies used by FADO in order to reach convergence.

After downloading FADO, the user must copy the editable files FADO.config and PLOT.config in the directory where the binary (executable file) is stored. FADO.config contains parameters controlling the fitting scheme and PLOT.config contains the parameters defining the graphical output.

Various parameters can be provided by the user when running the code, in order to get optimal fits to the spectrum. The mandatory parameters that should be provided are: the spectrum to be modelled (*-i*), the path to the directory containing the SSP base and the library of the SSPs to be used for the spectral modelling (*-b*), the resolution i.e. the FWHM across wavelength in $\text{\AA}$ of the input spectrum (*-r*), the distance to the galaxy in Mpc (*-d*), the spectral range used in the modelling and for which the synthetic best-fitting model is exported together with the wavelength step-size (*-s*). It is recommended for λ -step to have a value that is by a factor ~ 2.35 smaller than the mean FWHM resolution of the spectrum. Secondary optional parameters include various extinction laws (Allen (1976), Calzetti (2001, PASP, 113, 1449C), Cardelli, Clayton and Mathis (1989, ApJ, 345, 245C), Fitzpatrick (1986) for the LMC, Gordon et al. 2003 - SMC Bar, LMC SuperShell, LMC Average, Prevot et al. (1984) and Bouchet et al.

(1985) for the SMC, Seaton (1979) plus Fitzpatrick (1986) for the MW), the assumed physical conditions for the nebular component, the flux units in $erg/(s * cm^2)$, the redshift of the galaxies and the verbosity level (from 0 to 10). The spectrum, that should be both flux and wavelength calibrated, can be provided to FADO either as an ascii or as a fits file. When using an ascii table, the first column must contain the wavelength information in $\text{\AA}$, the second column the flux information in $erg/s * cm^2$ and the third column the error information. If the error spectrum is not provided, FADO will estimate it automatically. It is advised that the input spectrum should be de-redshifted, even though the software does not require it. It is also expected that the input spectrum was corrected for galactic foreground extinction. The rebinning of the spectrum to a constant wavelength step is however not advised, as this is done by the software itself, by using a flux-conserving routine. It is also recommended that the redshift option should be used between $+/- 1000 km/s$ for emission line spectra [27].

Having all of the aforementioned options in mind, FADO was run for the CLASH-VLT VIMOS galaxy spectra as follows. The input VIMOS spectra, provided to FADO with the option *(-i)*, were already flux and wavelength calibrated as well as corrected for galactic foreground extinction. The spectra were provided as fits files, and the software automatically estimated the error spectrum.

The optional redshift parameter was also used when running the code, which includes the minimal recessional velocity, the maximal recessional velocity and $\Delta_{velocity}$. The velocities of the investigated galaxies were calculated with the following equation:

$$v = c \cdot z \quad (4.2)$$

FADO was then provided with the redshift parameter as follows: $v_{max} = v + 1000[km/s]$, $v_{min} = v - 1000[km/s]$ and $\Delta_v = 10$.

The FWHM across wavelength interval in $\text{\AA}$ for the input spectrum, was also provided to FADO, with a value of $r=10$.

Another parameter relevant for the software is the distance to the investigated galaxies. The luminosity distance was calculated for this purpose, by means of a python code, using the *astropy.cosmology* package of *astropy*. The used cosmological parameters are in accordance to the Λ CDM model: $H_0 = 70 km Mpc^{-1}s^{-1}$, $\Omega_{m,0} = 0.27$, $\Omega_{\Lambda,0} = 0.73$. The luminosity distance was computed based on the galaxy's redshift. This parameter is defined in terms of the relationship between the absolute magnitude M and apparent magnitude m of an astronomical object as [28] :

$$M = m - 5(\log_{10} D_L - 1) \quad (4.3)$$

or in terms of the relationship between bolometric flux S and bolometric luminosity L as [28]:

$$D_L = \sqrt{\left(\frac{L}{4\pi S}\right)} \quad (4.4)$$

Another parameter used when running FADO was the spectral range: $\lambda_{min} = 4800\text{\AA}$, $\lambda_{max} = 10000\text{\AA}$ together with the wavelength step $\Delta_\lambda = 2$.

Another parameter relevant for FADO is the extinction law. The Calzetti et al. 2001 extinction law, extended to the FUV, was chosen for this purpose. The presence of dust in galaxies removes half or more of the stellar energy and is responsible for extinction. The extinction is the sum of two physical processes: absorption and scattering by dust, whereas attenuation refers to the net effect induced by dust in a complex geometrical distribution. As both the light sources and the dust have extended, complex distributions, their relative location has a major impact on absorbed and scattered light. Dust scattering on the line of sight will produce a greyer overall attenuation than scattering out of the line of sight, and the emerging SED will thus be bluer. The different geometrical relation between dust and stars produces huge differences in the output SED, with generally a foreground screen of dust producing the largest reddening and dimming. This is the typical situation encountered when studying galaxies, and attenuation becomes thus a very important parameter that one should take into account when analysing galaxy spectra. With a simple geometry, dust can be treated as a foreground screen, and the attenuation can be described as:

$$f_{int}(\lambda) = f_{obs}(\lambda)10^{0.4\kappa^e(\lambda)(E-V)_{star}} \quad (4.5)$$

where $\kappa^e(\lambda)$ is an effective attenuation curve to be applied to the observed stellar continuum SED, $f_{obs}(\lambda)$ of a starburst galaxy to recover the intrinsic SED $f_{int}(\lambda)$. The effective attenuation curve can be expressed as:

$$\kappa^e(\lambda) = 2.659(-1.857 + 1.040/\lambda) + 4.05 \quad (0.63\mu m \leq \lambda \leq 2.20\mu m) \quad (4.6)$$

or

$$\kappa^e(\lambda) = 2.659(-2.156 + 1.509/\lambda - 0.189/\lambda^2 + 0.011/\lambda^3) + 4.05 \quad (0.12\mu m \leq \lambda \leq 0.63\mu m) \quad (4.7)$$

$E(B - V)_{star}$ stands for the stellar continuum colour excess, which has a lower value than that of the ionised gas, and it can be expressed as follows:

$$E(B - V)_{star} = 0.44 \cdot E(B - V)_{gas} \quad (4.8)$$

Observations have shown that galaxies in the local and high-redshift universe ($z < 2$) are only moderately opaque, and extreme values of the opacity are found only in the more active systems. Table 4.1 includes the effective extinction values for galaxies of different morphological

types in the local universe. For $z \sim 1$ galaxies, the dust opacities cover a range similar to that of local star-forming and starburst galaxies, even though the distant galaxies tend to be more luminous and more active on average. Calzetti et. al 2001 also postulated that luminous, intermediate- to late-type spirals are dustier than elliptical galaxies, by 1.01.4 mag in the UV and than irregulars by 0.50.8 mag. Luminous galaxies are also more metal rich and dust rich than their faint counterparts. Dust opacity was also found to increase with thermal and non-thermal activity [29].

Another important parameter, that is relevant when running FADO, is the simple stellar population library used for the spectral modelling. For this work, the library of SSP spectra from Bruzual and Charlot et al. 2003 was used. This model allows the computation of the spectral evolution of stellar populations of different metallicities, with ages between $10^5 - 2 \cdot 10^{10}$ years, at a resolution of 3 Å FWHM across a wavelength range from 3200 Å to 9500 Å. The spectral evolution can also be derived for a larger wavelength range, from 91 Å to 160 μm , but for a lower resolution. This SSP model includes theories of stellar evolution and a prescription for thermally-pulsing AGB stars. The model manages to reproduce the observed optical and near-infrared colour magnitude diagrams of galactic star clusters with different ages and metallicities, as well as the typical galaxy spectra obtained from the SDSS Early Data Release. The model also enables the analysis of absorption-line strengths in galaxies with stars of different ages. It can also recreate the observed strengths of Lick indices as well as several spectral features that do not depend on element abundance ratios, but it has small problems reproducing those indices whose strength depends on abundance ratios. This type of spectral fits can be very useful in constraining the star formation histories and metallicities of galaxies [30].

Having all the aforementioned parameters in mind, FADO can be run for each individual spectrum in the terminal with the following command:

```
./FADO -i input/sc_R2248_000067452_clean.fits -o output -b SSPs/Base.BC03.L
-s 4800 10000 2 -r 10 -v 101798 103798 10 -d 1263.5 -e CALR
```

This is an example of a FADO run for a cluster galaxy with the ID 67452, at a redshift of $z = 0.3422$.

After all the aforementioned parameters were provided to FADO for each of the investigated VIMOS galaxies, the software computed a manifold of physical quantities for each galaxy with a sufficiently well resolved spectrum.

The primary and secondary output quantities of FADO were stored in 4 different FITS files:

1. The 1D spectrum contains the λ -dependent quantities such as the de-redshifted and rebinned observed spectrum, the error spectrum, the mask with fake features and the best-

fitting synthetic SED together with the average, median and standard deviation of the obtained solutions. Also contained within this file is the stellar and nebular SED which are composing the best-fit spectrum together with the line-spread function.

2. The Statistics file includes the mean stellar age and metallicity, expressed in both linear and logarithmic form, the "ever formed" and "presently available" stellar mass, the mass fraction of stars younger than 100 Myr, 1 Gyr and 5 Gyr, the rate of LyC photons that can ionize hydrogen and single/double ionizing helium.
3. The Emission-Lines file includes both the measured and modelled fluxes as well as the equivalent widths for 51 emission lines in the spectral range between 4500 Å and 8617 Å: $[OII]_{\lambda 3727,3729}$, $H\gamma$, $H\delta$, $[OIII]_{\lambda 4363}$, $H\beta$, $[OIII]_{\lambda 4959}$, $[OIII]_{\lambda 5007}$, $[NII]_{\lambda 5755}$, $[OI]_{\lambda 6300}$, $[NII]_{\lambda 6548}$, $H\alpha$, $[NII]_{\lambda 6584}$, $[SII]_{\lambda 6716}$, $[SII]_{\lambda 6731}$, etc. The uncertainties regarding the flux measurements are also included within this file.
4. The Population Vector file includes the full population vector for all individuals. This population vector contains parameters such as the light- and mass contributions (x_j, μ_j) of SSPs, the kinematical parameters and the stellar and nebular extinction [27].

Besides the 4 aforementioned output quantities of FADO, which are stored as FITS files, the code also offers a graphical output, stored as an EPS file, see figure 4.4. The colour coding from the graphical output offers information on whether specific physical quantities could be determined or not: if displayed in red, then the different quantities were successfully measured (eg.: T_e, n_e , $[NII]/H\alpha$, $[OIII]/H\beta$ and $EW(H\alpha)$). If the different physical conditions were not determined, then they will be displayed in light blue. The quantities related to the properties of the stellar population are displayed in black. Figure 4.4 shows an example of a spectral fit with FADO for an RXJ2248 cluster member with the ID 67452 and a redshift of $z=0.3422$. The upper panel shows the VIMOS spectrum, represented by the orange curve, together with the best-fitting synthetic SED, which is composed of stellar and nebular continuum emission (dark grey and red curves respectively), represented by the blue curve. The values for the electron temperature T_e and density n_e as computed by FADO from the emission lines can be seen in the upper part of this panel, together with a given probability π of the system to be characterised as an SF, composite, LINER or Seyfert galaxy in BPT diagnostic-diagrams. Below the first large panel, one can visualise the residuals between fitted and observed spectrum. The upper right panel shows the luminosity fraction at the normalised wavelength whereas the lower right panel shows the stellar mass fraction of the SSPs which compose the best-fitting population vector as a function of their age. The colour codes describe the metallicities and the vertical bars the $\pm 1\sigma$

Table 4.1: This table shows the average dust extinction in local galaxies. ^a stands for the fraction of the bolometric radiation absorbed and/or scattered by dust. ^b stands for the face-on attenuation at the specified wavelength/band. ^c stands for inclination-averaged attenuation for the disk and irregular galaxies [29].

Galaxy Type	L_{dust}/L_{bol}^a	$A_{0,15,f}^b$	$A_{0,15}^c$	$A_{B,f}^b$	A_B^c	$A_{I,f}^b$	A_I^c	$A_{K,f}^b$	A_K^c
E/S0	0.05-0.15	0.10-0.20		0.05-0.10		0.02-0.04		< 0.02	< 0.15
Sa-Sab	...	0.40-0.65	0.90-1.25	0.20-0.40	0.50-0.75	0.10-0.15	0.30-0.40	< 0.05	< 0.15
Sb-Scd	0.45-0.65	0.60-0.80	1.20-1.45	0.30-0.50	0.65-0.95	0.15-0.20	0.40-0.45	0.05-0.10	0.15-0.20
Irr	0.25-0.40	0.30-0.45	0.60-0.75	0.10-0.15	0.30-0.40	~ 0.05	~ 0.15	<0. 02	< 0.06

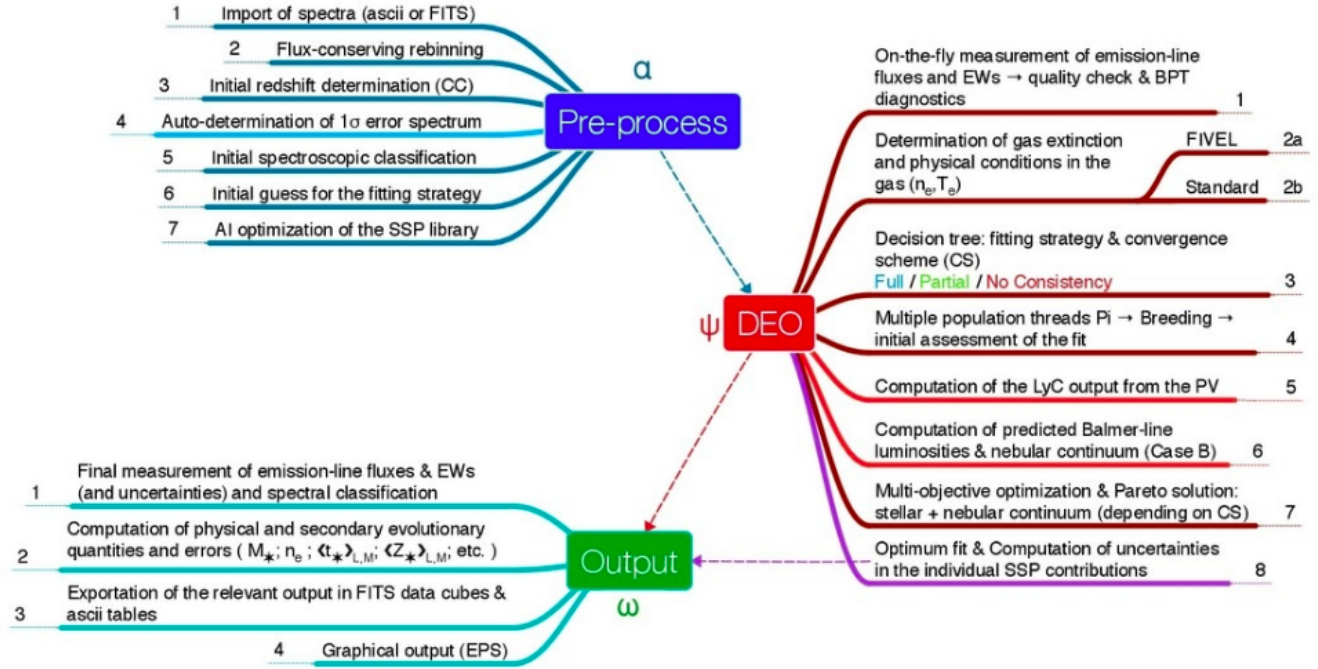
uncertainties. The thin-grey vertical lines which connect both diagrams coincide to the ages of the SSPs from the used library. Various physical parameters also appear in this output such as the fluxes and equivalent widths for $H\alpha$ and $H\beta$ emission lines, as well as the logarithmic values of the emission line ratios: $[OIII]/H\beta$, $[NII]/H\alpha$. Other parameters such as the redshift, the distance, the mass, the metallicity, the age and so on can be found within this figure.

The values for the emission line fluxes as computed by FADO were compared to the fluxes measured with splot in IRAF, see figure 4.5. Only the measurements for the RXJ2248 cluster members are shown here. The measurements of the line fluxes provided by both softwares are in good agreement to each other, except for a few out-liners which were assigned a quality flag $f=2$ or $f=3$ when investigated in splot and VIPGI, meaning that one or more line fluxes could not be measured. A larger scatter can be seen when comparing the 2 measurements for the flux ratio $[NII]/H\alpha$. This is due to the fact that the $H\alpha$ and $[NII]$ emission lines fall in that part of the spectrum where sky-lines are more abundant, making its flux measurements more complicated. It is also worth mentioning that when using splot in IRAF, I was able to measure emission line fluxes for more galaxies than when using FADO, as the latter one had problems fitting the template SEDs for a large number of spectra which showed fairly weak ELs.

4.2 Mass estimation

The masses of the investigated galaxies were derived using the LePHARE code of Arnouts and Ilbert et al. 2011, which is a software specially designed to compute photometric redshifts using the technique of SED fitting. This technique is based on fitting the global shape of the spectra and on the detection of strong spectral signatures. A set of filters, that highlight strong spectral

Figure 4.3: This diagram illustrates a schematic view of FADO and the strategies for reaching convergence.



features such as the $4000\text{\AA}$ break or the Lyman break, should be chosen in order to get a better accuracy. The observed photometric SEDs are then compared to template SEDs obtained from a set of reference spectra, using the same photometric system. These template SEDs can be either synthetic or observed. SED fitting thus matches observed galaxy fluxes, at a specific photometric band, with a library of reference fluxes, using standard χ^2 minimization procedure:

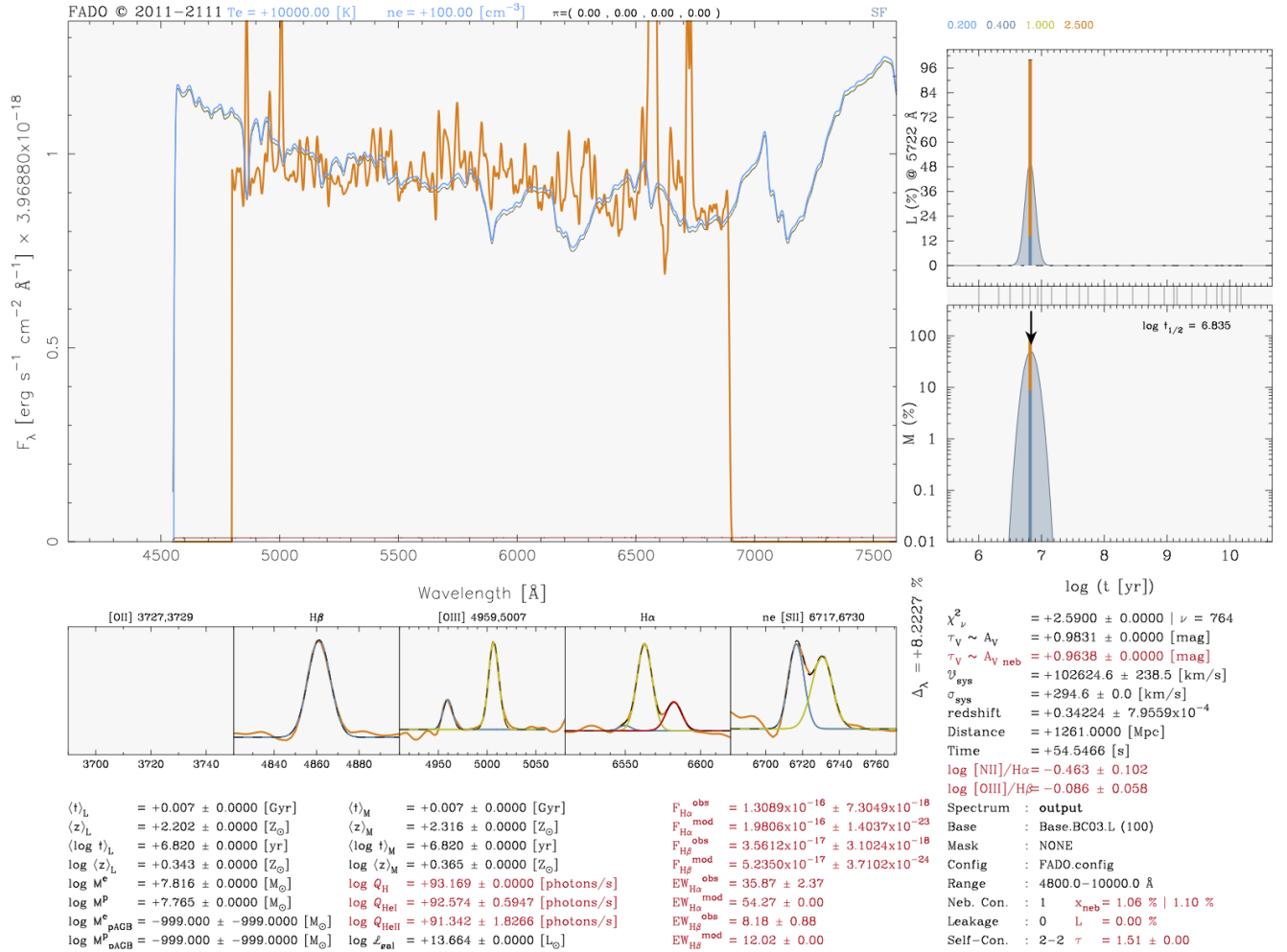
$$\chi^2(z) = \sum_{i=1}^{N_{\text{filters}}} \left[\frac{F_{\text{obs},i} - b \cdot F_{\text{temp},i}(z)}{\sigma_i} \right]^2, \quad (4.9)$$

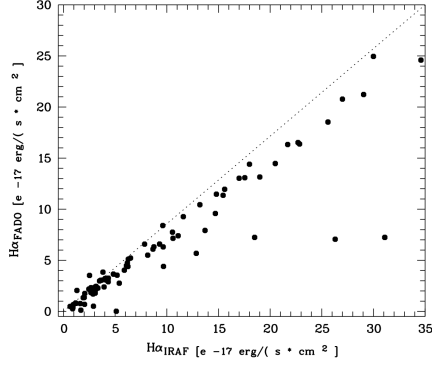
where $F_{\text{obs},i}$, $F_{\text{temp},i}$ and σ_i are the observed and template fluxes and their uncertainty in filter i , respectively, and b is the normalisation constant. This approach allows the derivation of several physical properties of galaxies such as their photo- z , SFH, masses, etc, depending on the used SED library and on the used code [31].

4.2.1 LePhare of Arnouts and Ilbert et al. 2011

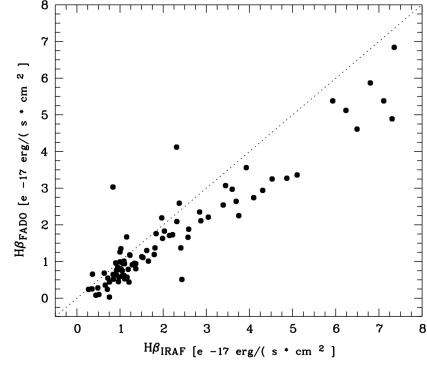
Lephare stands for PHotometric Analysis for Redshift Estimate and is a code designed to fit stellar population synthesis models to photometric data, performing thus SED fitting, in order to derive photometric redshifts and other physical parameters for galaxies. The code is composed

Figure 4.4: This figure shows an example of a spectral fit with FADO for a R2248 cluster member at a redshift of $z=0.342$. The VIMOS spectrum is represented by the orange curve, while the best-fitting synthetic SED, which is composed of stellar and nebular continuum emission (dark grey and red curves respectively), is represented by the blue curve. Below the first large panel one can observe the residuals between fit and observed spectrum. The upper right panel shows the luminosity fraction at the normalised wavelength whereas the lower panel right shows the stellar mass fraction of the SSPs which compose the best-fitting population vector as a function of their age.

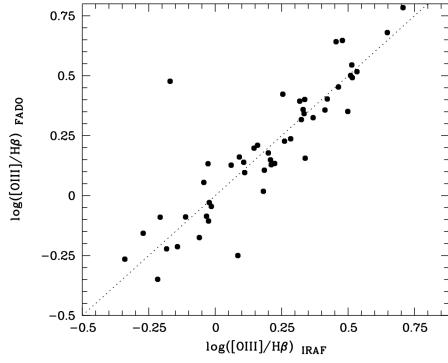




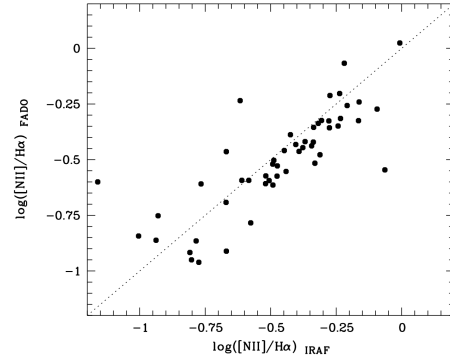
(a) $H\alpha$ fluxes FADO vs IRAF.



(b) $H\beta$ fluxes FADO vs IRAF.



(c) $[OIII]/H\beta$ line ratios FADO vs IRAF.



(d) $[NII]/H\alpha$ line ratios FADO vs IRAF.

Figure 4.5: This plot shows the difference between emission line fluxes and line ratios as measured with FADO and splot in IRAF for the R2248 cluster members.

of a set of FORTAN commands, which incorporate the standard χ^2 minimisation method, that offers the best match to a reference set of spectral templates for the given photometric data. The structure of LePhare can be divided into three parts:

1. The first phase where the user chooses the SED libraries and filter bands in order to compute theoretical magnitudes.
2. The photometric redshift program, based on the χ^2 fitting method. This program also computes additional physical parameters for the investigated object such as the mean age, the SFR, the stellar mass and uncertainties.
3. A simulation program, that produces multi-colour catalogues.

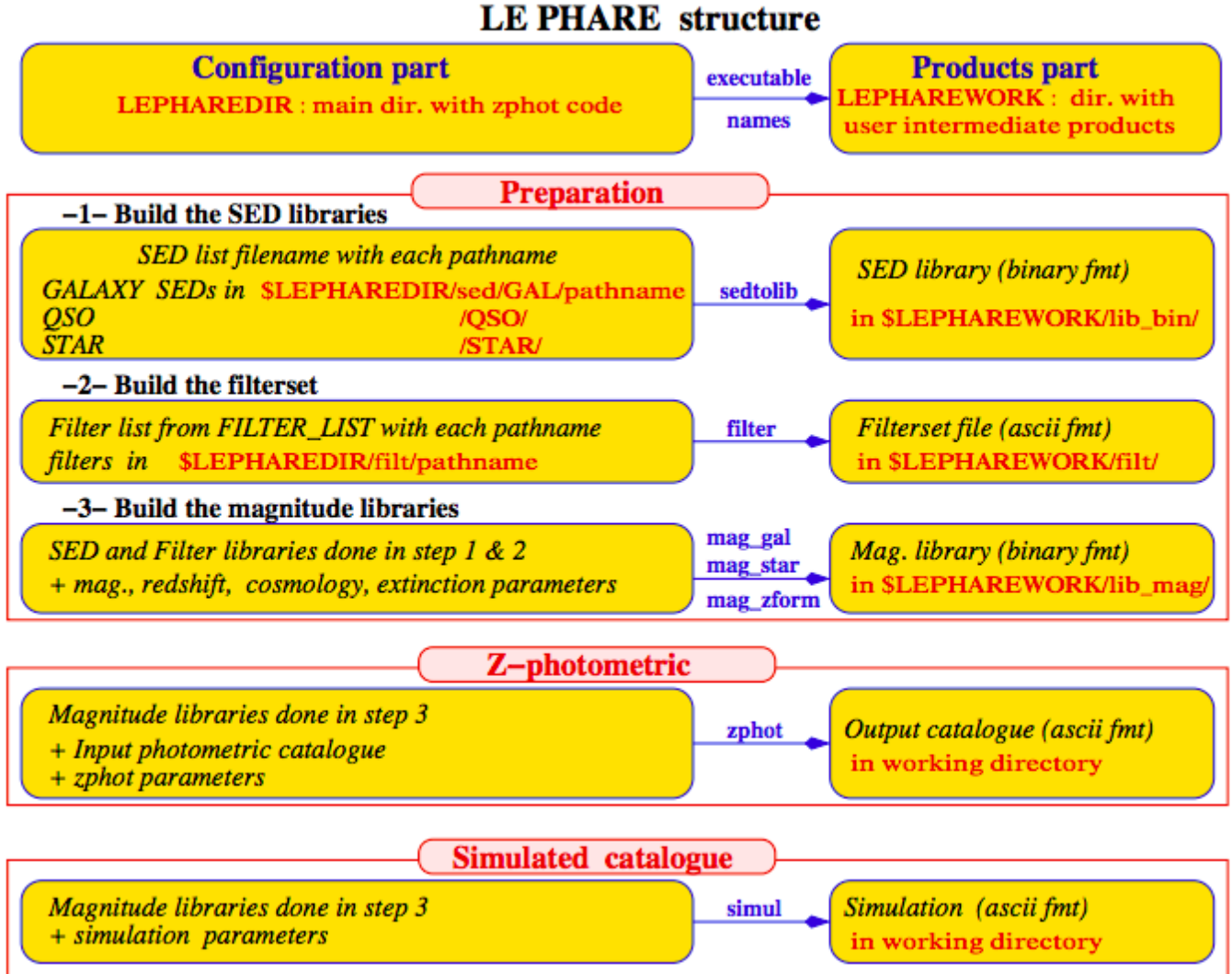
Figure 4.6 shows an overview for the structure of LePhare code.

The photometric data provided to LePhare consists of WFI UBVRIZ magnitudes for 636 galaxies together with the errors for each filter. The data is provided to LePhare by means of an input catalog with 13 columns: the galaxy ID together with the observed magnitudes and errors in the 6 WFI bands. When the catalog is provided in this form, one needs to select the parameter **CAT TYPE=SHORT**. It is also important that the filters in the input catalog follow the same order and include the same number of couple (mag, error) values as in the library, which is defined by the parameter **FILTER_LIST**. In appendix A, we give more details to the preparation of the input catalog, as this file needs to be edited in order to compute the synthetic absolute magnitudes in the Subaru filters.

The information to all the parameters needed to run the code can be found in 2 configuration files: one file is responsible with the input parameters and the other one with the information present in the output. The configuration file responsible with the input parameters is called **zphot.para**, and the one responsible with the output quantities is called **zphot_output.para**. The parameters that should be provided to LePhare, and which are found in the configuration file **zphot.para**, can be divided as follows: the parameters responsible with the creation of libraries from the SED list, the parameters describing the filters, the ones responsible with the computation of the theoretical magnitudes and the parameters used for the estimation of the photometric redshift.

The used population synthesis models are based on the galaxy library of SSP spectra from Bruzual and Charlot et al. 2003, see the previous section for details. The parameter **GAL_SED** is responsible with the used galaxy library of SSP spectra. The additional stellar and QSO libraries consist of a combination of different SED models, and were left as default. The QSO SEDs incorporate synthetic QSO spectra, the Mari Polletta templates from SWIRE, the Mara

Figure 4.6: This diagram illustrates a schematic view of LePhare [32, 33, 34].



Salvatto Hybrid models from COSMOS and a various set of composite SEDs, and is provided to LePhare by means of the **QSO_SED** parameter. The stellar library consists of a combination of various SED libraries, such as the stellar SEDs from Pickles (1998), the low mass stars library from Chabrier et al. (2000), white dwarfs from Bohlin et al. (1995) and spectro-photometric standards from Hamuy et al. (1992, 1994). The parameter responsible with the stellar SEDs is **STAR_SED**. For the cluster members with redshifts of ~ 3.5 , the templates were fit for stellar ages between 1 Gyr and 11 Gyrs. This information is provided to the code through the parameter **AGE_RANGE**. This premise was based on the fact that at this respective redshift, the universe was 9.821 Gyrs old and most of the stellar mass was assembled by that time. For the field population, a higher range of stellar ages was used, between 1 and 13 Gyrs, as these

galaxies span a larger redshift range, between 0.1-0.9. These parameters are the ones responsible with the generation of the libraries from the SED list.

The parameter describing the filters is **FILTER_LIST**, and is represented by a list: *wfi/U.pb*, *wfi/B.pb*, *wfi/V.pb*, *wfi/R.pb*, *wfi/I.pb*, *wfi/Z.pb*. All of these 6 files contain the wavelength and transmission information for the respective filter. The filter program puts together a list of filter response curves, and applies some transformations according to the nature of the filters.

As next, one should provide LePhare the parameters responsible with the computation of the theoretical magnitudes. This program measures the magnitudes for the galaxy sample. For the given set of filters and an input SED library, the magnitudes are computed at different redshifts as defined by the redshift step. The redshift step was chosen as follows: $z_{min} = 0.3$, $z_{max} = 0.4$, $\Delta z = 0.05$ for the cluster galaxies and $z_{min} = 0.1$, $z_{max} = 1$, $\Delta z = 0.05$ for the field population. This information is provided to the code by means of the parameter **Z_STEP**. The magnitude type was set to be *AB*, and is provided to LePhare by means of the parameter *MAGTYPE*. The used cosmological parameters are in accordance to the Λ CDM model: $H_0 = 70 \text{ km Mpc}^{-1} \text{ s}^{-1}$, $\Omega_{m,0} = 0.27$, $\Omega_{\Lambda,0} = 0.73$, and based on them, the code will reject models older than the age of the universe. This information is provided through the parameter **COSMOLOGY**. The model range for extinction, which is given by the parameter **MOD_EXTINC**, was chosen to be between 0 and 30, and the chosen extinction law, given by the parameter **EXTINC_LAW** was that of Calzetti et al. 2001, see the previous section for more details. The extinction law will be applied to a range of SED models specified by the model range for extinction. In order to avoid overfitting, the number of extinction $E(B-V)$ values, provided through the parameter **EB_V**, were limited to 0.1, 0.3, 0.5.

Coming to the parameters responsible for the computation of the photometric redshift, as first one should provide the input catalog containing the observed magnitudes in the 6 WFI filters together with the errors, with an additional description of the catalog, such as the input type (magnitude), the magnitude type (AB), and the order of the columns of the input catalog (magnitude, error). The parameters responsible with this information are: **CAT_IN**, **INP_TYPE**, **CAT_MAG**, **CAT_FMT** respectively. As next one should specify the name of the output file through the parameter **CAT_OUT**, where all the computed physical parameters for the investigated galaxies will be stored. LePhare offers the user the possibility to chose which physical parameters should be computed: the photometric redshift and its errors, parameters describing the χ^2 model fitting, the absolute magnitudes, the distance, the K-corrections, the ages, masses, SFRs, etc. All this information is contained in the **zphot_output para** configuration file, and the user can comment/uncomment which parameters should be computed by writing/deleting

the symbol # in front of each row of this file. The χ^2 analysis is then based on the input catalog. Some prior information can be added, in order to constrain the χ^2 fitting procedure. One can restrict the redshift, extinction ranges, the expected mass and absolute luminosity ranges. The mass and magnitudes range were chosen as follows: $\log(\frac{M_{min}}{M_{\odot}}) = 6$, $\log(\frac{M_{max}}{M_{\odot}}) = 12$; $M_{abs,min} = -14 \text{ mag}$, $M_{abs,max} = -26 \text{ mag}$. The parameters responsible with the mass and magnitude ranges are: **MASS_SCALE** and **MAG_ABS**. To derive absolute magnitudes, a parameter describing the reference number for the observed magnitude in a specific filter should also be provided to LePhare. In order to check which of the filters reach the deepest in terms of faint objects, a plot was computed, containing on the x-axis the observed magnitude in a filter and on the y-axis the error in the respective filter, see figure 3.2. The observed magnitudes in the R-filter were used to compute the absolute magnitude, and this information was provided to LePhare by means of the **MAG_REF** parameter. This choice is argued by the fact that the R-filter is the most sensitive towards low values for the observed magnitudes, reaching down to a magnitude of 23, and it also has the smallest scatter in the error-observed magnitude plot, see figure 3.2. The code also asks whether the redshift should be kept fixed or not when fitting the SED models. We have chosen a fixed redshift in order to search for the best models, by means of the parameter **ZFIX = YES**. LePhare also allows the user to specify different methods to compute the absolute magnitudes. The magnitudes are then automatically computed in all the filters provided by the filter list.

There are 5 methods available for the computation of the absolute magnitudes, given by the parameter **MABS_METHOD**:

1. A direct method to estimate the absolute magnitude in a respective filter based on the apparent magnitude measured in the same filter, but which is very sensitive to the k-correction and to systematic effects in the measurement of the apparent magnitude, thus being less accurate.
2. A method which is not that strongly dependent on the template. For example, in order to compute the absolute magnitude in filter B for an observed galaxy at a redshift of $z \sim 0.7$, one uses the observed apparent magnitude in the filter I, which is selected to be as follows:

$$\lambda(I) = \lambda(B) \cdot (1 + z) \text{ at } z \sim 0.7 \quad (4.10)$$

$$B_{abs} = I_{obs} - DM(z = 0.7) - (k_{cor}(I) + (B - I))_{abs}^{temp} \quad (4.11)$$

3. A method that measures the absolute magnitudes in all the bands using the observed apparent magnitudes taken in the same observed filter.

4. A method that measures the absolute magnitudes directly from the best-fit template. This method is however strongly model dependent.
5. This method measures absolute magnitudes, by imposing a redshift dependency of the filter. This is the non-automatic version of method 2.[**32**, **33**, **34**].

For this work, method 2 was chosen to estimate the absolute magnitudes. The magnitudes are derived in the reference band *Ref*, from the apparent magnitude in the observed band *Obs* as follows:

$$M_{Ref} = m_{Obs} - DM(z, H_0, \Omega_m, \Omega_\Lambda) - KC(z, SED) \quad (4.12)$$

with DM the distance modulus and KC being defined as follows:

$$KC(z, SED) = (k^{Ref}(z) + m_{Obs}(z) - m_{Ref}(z))^{SED} \quad (4.13)$$

where k^{Ref} stands for the K-correction in the reference band. The reference band was chosen to be the R-band, by means of the input parameter **MABS_REF**. The *Obs* band was chosen automatically to be as close as possible to the *Ref* band redshifted in the observer frame, in order to limit the template dependency. The deficiency of this method is that a systematic effect in the observed band will be propagated to the absolute magnitude, however, the choice of the reference band allows to reduce the filter set used for the observed apparent magnitudes [**35**]. LePhare also offers the possibility to get as an output the spectrum for each object (**SPEC_OUT**), as well as an output file with all the relevant values (**CHI2_OUT**): z , mod, χ^2 , E(B-V), etc, in addition to the output quantities specified in the configuration file **zphot_output para**. Synthetic Subaru BRz absolute magnitudes were also computed for the investigated galaxies with available photometric data. Details to the computation of the magnitudes in the Subaru filters can be found in appendix [A](#).

The code LePhare can be run in the terminal, after providing the aforementioned parameters in the configuration file, with the following commands:

```
export LEPHAREDIR=path to directory.../Lephare/lephare_dev/

export LEPHAREWORK=path to directory.../Lephare/lepharework/

cd $LEPHAREDIR/test

$LEPHAREDIR/source/sedtolib -t S -c ../config/zphot para

$LEPHAREDIR/source/sedtolib -t Q -c ../config/zphot para
```

```
$LEPHAREDIR/source/sedtolib -t G -c ../config/zphot para
```

```
$LEPHAREDIR/source/filter -c ../config/zphot para
```

```
$LEPHAREDIR/source/mag_star -c ../config/zphot para
```

```
$LEPHAREDIR/source/mag_gal -t Q -c ../config/zphot para
```

```
$LEPHAREDIR/source/mag_gal -t G -c ../config/zphot para
```

```
$LEPHAREDIR/source/zphota -c ../config/zphot para
```

After the run, LePhare will generate an output file containing all the information which the user requested in the output configuration file [32, 33, 34].

It is also worth mentioning that LePhare assumes a Chabrier (2003) Initial Mass Function (IMF) when computing stellar masses. The Chabrier masses for the investigated sample of galaxies were then converted to Salpeter IMF (1955) masses as follows:

$$M_{Salpeter} = M_{Chabrier} \cdot 1.7 \quad (4.14)$$

Pozzetti et al. 2007 found the factor of 1.7 to be a systematic median offset in the masses derived with the two different IMFs, Chabrier and Salpeter. This factor was also found to have a very small dispersion and a rather constant value for a wide range of SFHs [36].

4.3 Sample selection

As stated earlier, I was provided with a sample of ~ 700 reduced CLASH-VLT VIMOS galaxy spectra. Photometric data taken with the WFI of La Silla Observatory was also available for 637 CLASH-VLT galaxies, with corrections for galactic extinction. The parent sample will be divided into 3 main redshift bins: one redshift bin for the cluster members and other 2 for the field galaxies. When comparing cluster to field galaxies, the redshift bin for the field population will be restricted to $0.3 < z < 0.4$, in order to avoid any redshift induced bias.

4.3.1 Selection of cluster galaxies for metallicity study

The membership of galaxies to the RXJ2248 cluster was investigated as first by means of a histogram containing the redshift distribution of the sample galaxies. A diagram was plotted, showing on the x-axis the redshift range of $0.25 < z < 0.45$ and on the y-axis the underlying frequency distribution. This was done in order to see if there is a accumulation of galaxies at a specific redshift range, see figure 4.7. As can be seen from this diagram, there is an over-density

of galaxies at $0.33 < z < 0.36$, thus meaning that these galaxies are members of the CLASH-VLT cluster RXJ2248, which has a median redshift of $z \sim 0.348$ according to the literature. From the parent sample of ~ 700 galaxies, 178 have a redshift in the range $0.33 < z < 0.36$, making them RXJ2248 cluster members. The cluster membership is later tested by means of a phase-space diagram, see section 5.7.

After measuring the fluxes of the emission lines of interest for the cluster galaxies, quality flags were assigned to all the spectra, as described in section 4.1.2 ($f=1$: all line fluxes were measured, $f=2$: one line flux is problematic/could not be measured, $f=3$: 2 or more line fluxes are problematic/could not be measured). From 178 cluster galaxies, 61 were assigned with a quality flag $f=1$, meaning that they have secure flux measurements of the 5 emission lines. Another sample of 58 galaxies were assigned a quality flag $f=2$, making them less reliable for the metallicity study. The rest of 59 cluster members were all described by a quality flag $f=3$. 33 out of these 59 galaxies show no emission lines at all, meaning that they are actually early-type galaxies from the central region of the cluster. The other 26 galaxies with $f=3$ show only one emission line, generally the $H\alpha$ line, for which the flux could be measured.

To select a sample of galaxies for the metallicity study, some constraints on the signal to noise (S/N) were applied. The S/N in the $H\alpha$ line was required to be $S/N_{H\alpha} > 10$. For the [OII], $H\beta$, [OIII] and [NII] emission lines, the S/N was restricted to be $S/N > 2$. The rest-frame equivalent widths of $H\beta$ and $H\alpha$ were required to be as follows: $EW(H\beta) > 2\text{\AA}$ and $EW(H\alpha) > 3\text{\AA}$.

From the 61 cluster members with secure measurements, 59 met the aforementioned S/N criteria, whereas from the sample of 58 cluster galaxies with $f=2$, only 36 have the S/N in the aforementioned range. This work is primarily based on the 59 RXJ2248 cluster members, which have secure measurements of their emission lines, having a quality flag $f=1$. Table 4.2 contains the final number of galaxies selected for the metallicity study.

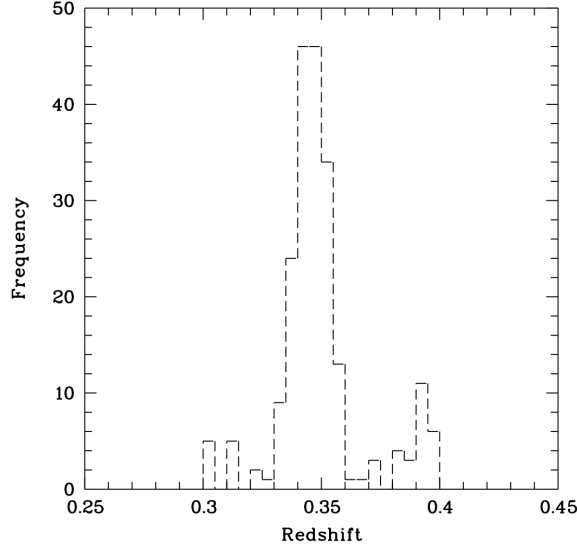
The masses of the cluster members span a range $8 < \log(M/M_{\odot}) < 11.2$, with a high fraction of galaxies found at $9 < \log(M/M_{\odot}) < 10$, as can be seen from fig. 4.8. This histogram shows the distribution of the masses of all the cluster members, as computed by LePhare.

From this sample, we have excluded AGN galaxies following the BPT diagnostic. More details to the distinction between star forming galaxies and AGNs are given in section 5.2.

4.3.2 Comparison sample of field galaxies

Out of ~ 700 CLASH-VLT galaxies, 443 were found to be part of the field population around the RXJ2248 cluster. This comparison sample was divided into two redshift bins: $0.01 < z < 0.33$ (low z bin) and $0.36 < z < 0.9$ (high z bin). From the low redshift bin, 161 galaxies have a

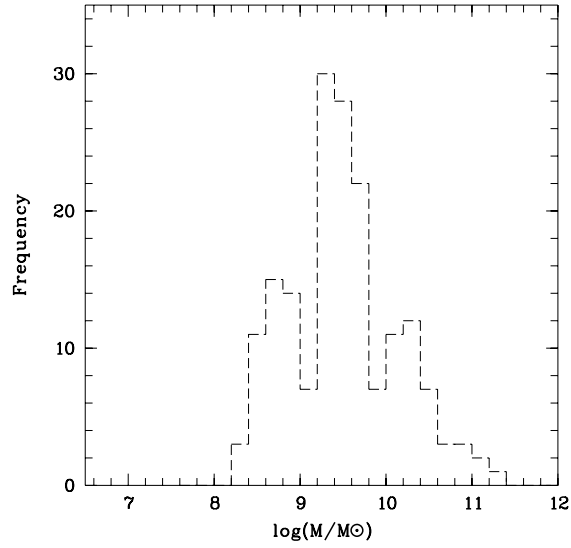
Figure 4.7: Histogram containing the redshift distribution of the investigated galaxies ($0.25 < z < 0.45$). An accumulation of galaxies can be seen around $z=0.35$. The RXJ2248 cluster has a $z = 0.348$, meaning that it's members will span a redshift range of $0.33 < z < 0.36$.



quality flag $f=1$, 34 a flag $f=2$ and 23 a flag $f=3$. The high redshift bin consists of 222 galaxies, out of which 168 have a quality flag $f=1$, 27 a quality flag $f=2$ and 9 a flag $f=3$. Only the galaxies described by a quality flag $f=1$ were chosen for the metallicity study. The same S/N constraints as described above were applied to this comparison sample. Because galaxies at redshifts higher than $z > 0.3$ also have measurements of the [OII] line flux, an additional S/N constraint was applied for this sample: $S/N_{[OII]} > 3$. 145 galaxies from the low redshift bin and 143 galaxies from the high redshift bin meet the aforementioned S/N criteria.

A second set of galaxies from the field around another CLASH cluster MACS J0416.1-2403 ($z = 0.4$), having the same redshift range as the RXJ2248 cluster members will also be used as a comparison sample. The spectra of these galaxies were registered with the VIMOS spectrograph as a part of the CLASH-VLT survey. My bachelor thesis was based on this data set, and due to the fact that some of these field galaxies fall exactly in the same redshift regime as the RXJ2248 cluster members, they were chosen as a comparison sample. From this sample of field galaxies, 7 have a redshift in the range $0.3 < z < 0.4$ and are described by a quality flag $f=1$. For these 7 galaxies, the $S/N_{H\alpha} > 5$ and the S/N in all other emission lines $S/N_{H\beta, [OIII], [NII]} > 3$ and the $EW(H\alpha) > 3\text{\AA}$. Table 4.2 shows the final number of galaxies selected for the metallicity study. For the comparison between cluster and field galaxies, we have restricted the redshift range of the field population to $0.3 < z < 0.4$, in order to avoid any biases.

Figure 4.8: Histogram containing the mass distribution of the investigated RXJ2248 cluster galaxies.



Galaxy sample	z	nr. galaxies $f=1$	nr. galaxies $f=2$	nr. galaxies $f=3$	Final sample after S/N constraint
RXJ2248 cluster galaxies	$0.33 < z < 0.36$	61	58	59	59, $f=1$; 36, $f=2$
field galaxies around RXJ2248, low z bin	$0.01 < z < 0.33$	161	34	23	145, $f=1$
field galaxies around MACSJ0416, middle z bin	$0.3 < z < 0.4$	7	0	0	7, $f=1$
field galaxies around RXJ2248, high z bin	$0.36 < z < 0.9$	168	27	9	143, $f=1$

Table 4.2: Final sample of cluster and field galaxies, selected for the metallicity study

Chapter 5

Results

5.1 Colour-Magnitude and Colour-Mass diagrams

It has been known for almost a century, thanks to the pioneering work of Edwin Hubble, that galaxies come in 3 basic morphological types: spiral galaxies which exhibit a disc of stars with spirals arms, elliptical galaxies which have a relatively smooth, featureless light distribution, being predominantly spheroidal, and irregular galaxies which show no noticeable symmetry nor an obvious central nucleus. Spiral galaxies are further on divided into 2 different classes - with a bar and bar-less - and are characterised by growing bulge sizes (SBc-SBb-SBa, Sc-Sb-Sa). The middle of Hubble's tuning fork is populated by lenticular galaxies (S0), which show bright central bulges, and their structure appears to be intermediate between elliptical galaxies and spiral galaxies. The Hubble sequence divides elliptical galaxies into different classes according to their ellipticity: E_n with $n = 10 \cdot \varepsilon$ and $\varepsilon = \frac{\text{majoraxis } a - \text{minoraxis } b}{\text{majoraxis } a}$ [37].

It has long been known that ellipticals tend to have redder colours than spirals (e.g. Hubble 1926), both locally and out to $z \sim 1$, as their stellar population is mainly composed of old, population II stars. Due to the fact that the stellar population of irregular galaxies, as well as the population of disks is constantly refurnished by newly formed massive, bright stars, these galaxies will generally exhibit bluer colours. The integrated optical colours of galaxies thus reflect their dominant stellar populations and also correlate with the morphological type. The age of a galaxy can also be appreciated by its colour, rather than its shape: young galaxies give off light mostly at blue wavelengths, revealing that they are actively producing new stars. Older galaxies put off most radiation infrared or red light, denoting old stellar populations. Colour indices and integrated magnitudes thus provide an important tool to study galaxy evolution, as they relate different physical parameters of galaxies, such as their morphology, age, metallicity, SFH, etc.

Recent studies have demonstrated that local galaxies show a strong bimodality in optical colour, dividing galaxies in the colour-magnitude diagram into the "blue cloud", and the "red sequence" with the "green valley" representing the transition zone between these two classes. Based on a large sample of SDSS galaxies, Strateva et al. 2001 showed that this dichotomy in the colour distribution is closely connected to the morphological type of the galaxy: the red sequence is mainly populated by early-type galaxies (ellipticals) whereas the blue cloud contains late-type galaxies (spirals and irregulars) [38]. However, this picture is not that simple, as this bimodality does not automatically imply a difference in morphological type. For eg., Franzetti et al. 2007 demonstrated that the red sequence is not purely populated by quiescent early-type galaxies. We know that the red sequence contains $\sim 60\%$ of the total stellar mass density of the local universe whereas the stellar populations of blue cloud galaxies account for $\sim$ half the local stellar mass budget. This suggests that the red sequence is populated by a significant fraction of late-type galaxies, with high-mass blue ellipticals being very rare [39]. Based on recent ultraviolet surveys, for eg., Kaviraj et al. 2007 postulated that not all red galaxies have stopped forming stars. This lead to the conclusion that the red sequence is composed by a heterogeneous family of systems which have followed different evolutionary paths. The "green valley" is on the other hand populated by intermediate-type galaxies (for eg. red-spirals) which have their star formation quenched, either due to their gas infall being shut off as an effect of the environment in which they reside, or due to the fact that both the gas supplies and gas reservoirs have been very quickly destroyed, because of mergers and/or AGN feedback. This transition zone is located at a colour index value of ~ 2 in the colour-magnitude diagram, with blue cloud galaxies located below this threshold and red sequence galaxies above, however, this threshold is strongly dependent on the photometric bands used to measure the apparent magnitudes [40]. For this master thesis, we have investigated a sample of emission-line galaxies, both from the CLASH cluster RXJ2248 and from the field, and as the spectra of these galaxies reveal emission features, which occur when gas is being ionized by young, massive stars, it means that they are still actively forming stars. Thus, these objects are expected to be blue cloud galaxies, as it can be seen from figures 5.1 and 5.2. Both of these plots show on the left-hand side a colour-magnitude and on the right-hand side a colour-mass diagram for the RXJ2248 cluster members. Figure 5.1 uses the observed magnitudes in the WFI filters while figure 5.2 uses the synthetic observed magnitudes in the Subaru bands, as computed by LePhare, see appendix A2 for more details. The colour codes stand for the different quality flags assigned to the ELs: the black points represent the galaxies described by a quality flag $f=1$, the blue ones the galaxies described by a quality flag $f=2$, and the red ones the galaxies described by a quality flag $f=3$.

These plots show that we have a uniform coverage in both luminosities and masses for the RXJ2248 members.

Fig. 1., from Maier et al. 2016 shows a colour-magnitude and a colour-mass diagram for another CLASH-VLT cluster - MACSJ0416 at a redshift of $z \sim 0.4$ - also using Subaru observed magnitudes. According to this diagram, the blue cloud reaches a maximum colour index value $B - R \sim 1.6$. When analysing fig. 5.2 from this work, some galaxies seem to exceed this threshold value of ~ 1.6 meaning that these objects represent the class of intermediate-type galaxies which are transiting towards the red sequence and currently populating the green valley. Galaxy spectra characterised by a quality flag $f=3$ have the highest B-R values at all masses, most of them surpassing the limit B-R value of the blue cloud. These galaxies show either weak (low S/N) or no emission lines, meaning that they have predominantly older stellar populations and little to no ongoing star formation. However, ~ 10 cluster galaxies, which have their spectra characterised by a quality flag $f=1$ and $f=2$, also lie in the green valley/ red sequence in the B-R vs R plane. These galaxies, as we will see in section 5.2, lie in the composite region of the BPT (Baldwin et al. 1981) diagram, between the theoretical curve of Kewley et. al 2002 and empirical curve of Kauffmann et al. 2003b, meaning that their main source of ionisation comes from both the stellar component and an AGN. Some of these objects were even classified as AGNs by the WHAN (Fernandes et al. 2011) diagram. Most of the galaxies populating the green valley/red sequence also fall in the quiescent, non - SF region of the sSFR-M plane, as we will see in section 5.3. This is an expected result, as the SFR decreases gradually from galaxies which populate the blue cloud to galaxies of the red-sequence.

Fig. 5.3 and 5.4 display on the left-hand side a colour magnitude and on the right-hand side a colour mass diagram for the comparison sample of emission line galaxies from the field around the RXJ2248 cluster. The observed magnitudes in the WFI B and R-bands were used for the upper two panels of both diagrams, whereas for the lower two panels, the synthetic observed magnitudes in the Subaru B- and R- bands were used, as computed with LePhare. Fig. 5.3 shows the colour magnitude and colour mass diagram for the sample of field galaxies from the low redshift bin ($0.01 < z < 0.33$) while fig. 5.4 shows the same, but for the field galaxies in the high redshift bin ($0.36 < z < 0.9$). The colour codes are the same as in the previous plots. As expected, most field galaxies populate the blue-cloud.

The choice of the colour index (B-R) for the colour-magnitude and colour- mass diagram is argued by the fact that the broad B band is sensitive to light from the blue part of the spectrum whereas the R filter passes the red light, and therefore, one can distinguish between the dominant stellar populations of the investigated galaxies.

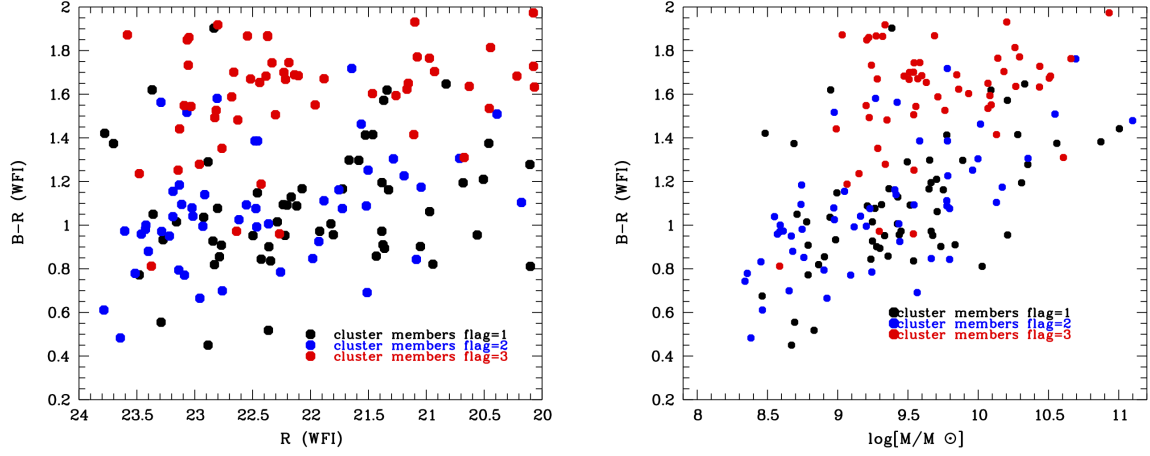


Figure 5.1: Colour-magnitude (left) and colour-mass (right) diagrams for the RXJ2248 cluster members. For both diagrams I used the observed magnitudes in the WFI filters. The colour codes represent the different quality flags, assigned to the spectra of these investigated galaxies, denoting the success in measuring the ELs fluxes.

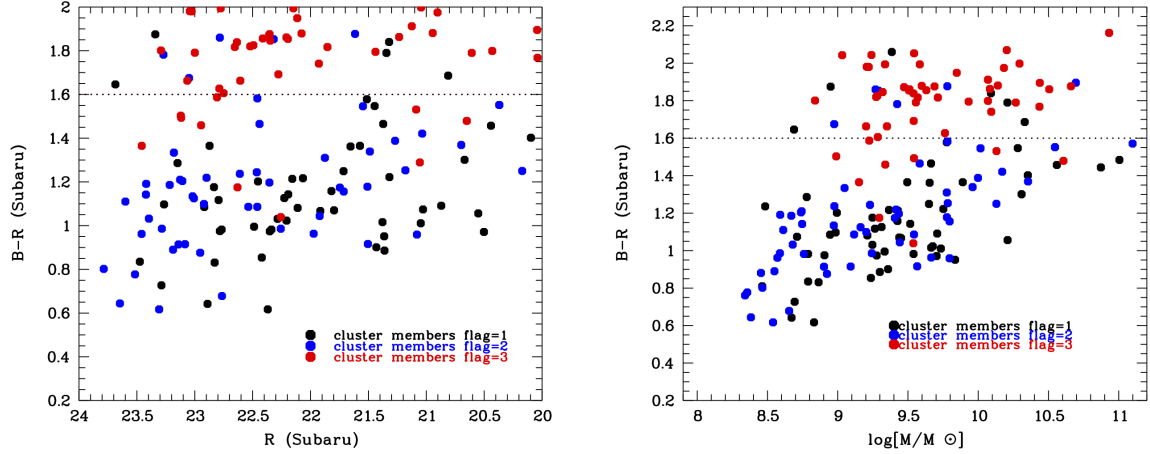


Figure 5.2: Color-magnitude (left) and color-mass (right) diagrams for the RXJ2248 cluster members. For both diagrams, the synthetic observed magnitudes in the Subaru filters were used, as computed by LePhare. The colour codes represent the different quality flags assigned to the ELs of these investigated galaxies.

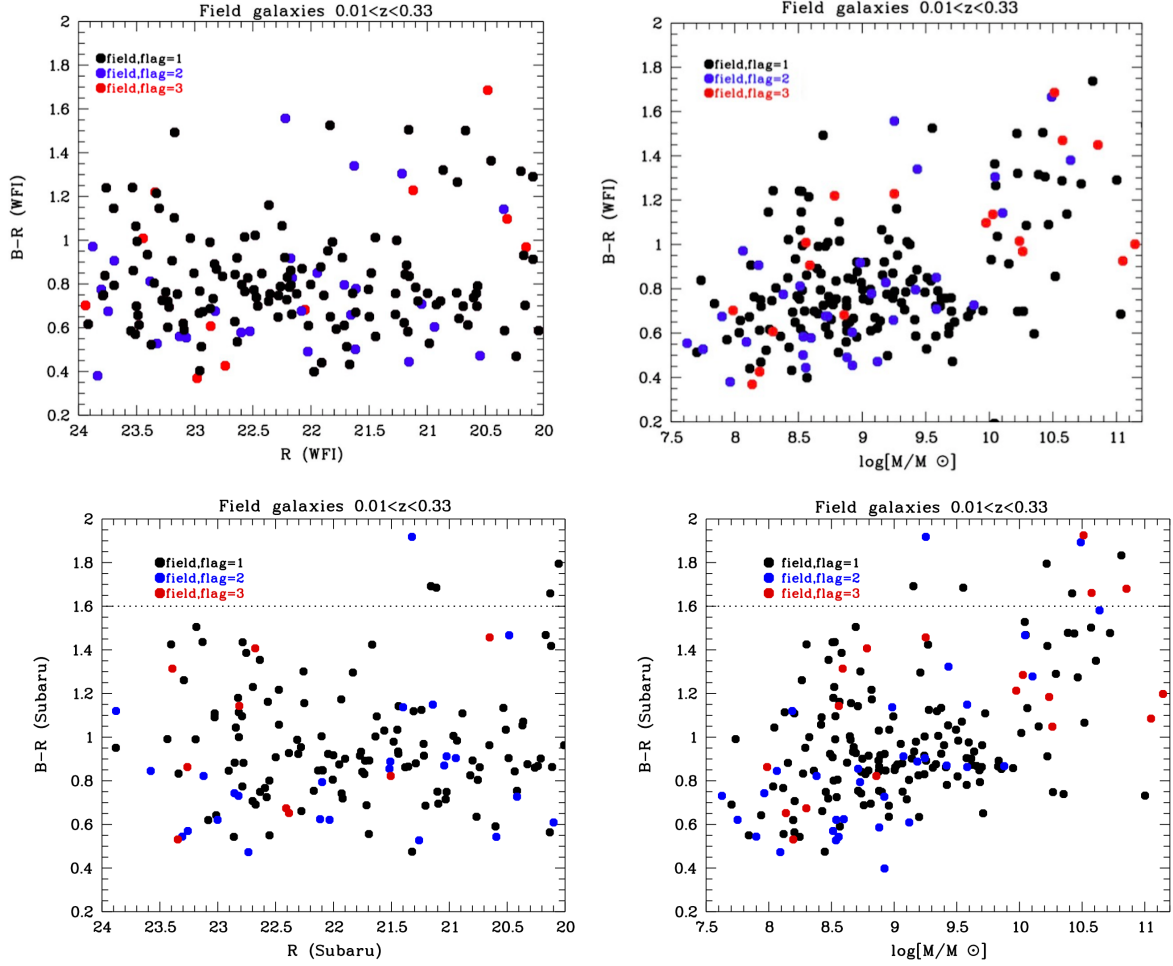


Figure 5.3: Color-magnitude (left) and color-mass (right) diagrams for the sample of field galaxies from the low redshift bin ($0.01 < z < 0.33$). For the upper two panels, the observed magnitudes in the WFI filters were used. The lower two panels use the synthetic observed Subaru magnitudes. The colour codes represent the different quality flags assigned to the spectra of the investigated galaxies.

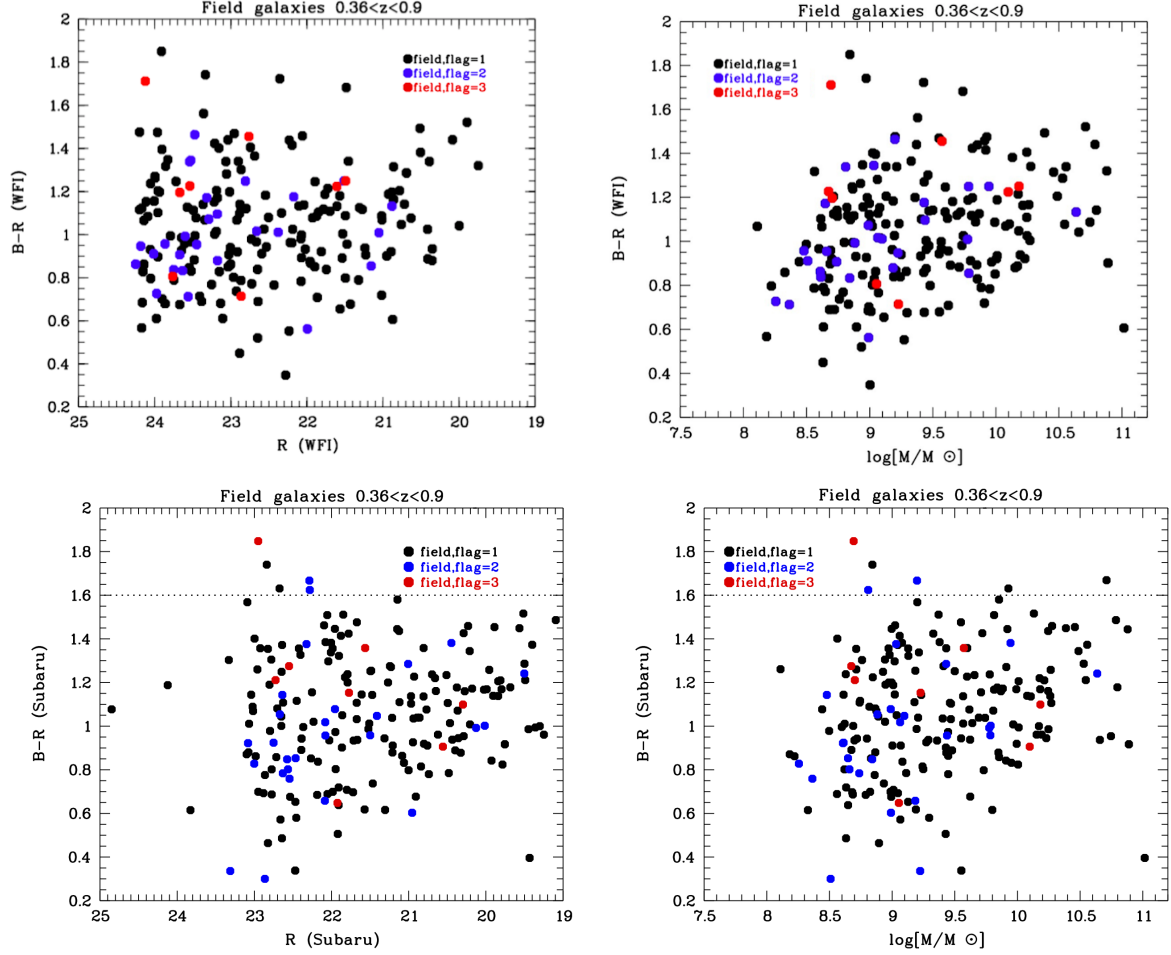


Figure 5.4: Color-magnitude (left) and color-mass (right) diagram for the sample of field galaxies from the high redshift bin ($0.36 < z < 0.9$). The observed magnitudes in the WFI filters were used for the upper two panels, while for the lower two ones, the synthetic Subaru observed magnitudes were used. The colour codes represent the different quality flags assigned to the spectra of the investigated galaxies.

5.2 Star forming galaxies and Type II AGNs

AGNs (Active Galactic Nucleus) can be described as compact regions at the centre of galaxies, that have a much higher than normal luminosity over the whole electromagnetic spectrum, due to the accretion of mass by a supermassive black hole. They are strong emitters at X-ray, UV, optical and radio wavelengths, showing variable luminosity of time-scales ranging from hours to years.

AGNs were first observed by Karl Seyfert in 1943, who studied spiral galaxies with starlike nuclei and strong emission lines in their spectra, realising that these galaxies form a distinct class of objects. Later on, AGNs were classified into 5 distinctive types of objects based on their rate of accretion and viewing angle : Seyfert 1 and 2, Quasars and QSOs, Blazars (BL Lacs), LINERS and Radio galaxies.

The unified model of AGNs explains this wide variety of features discerned in different classes in terms of the anisotropic geometry of the black hole's immediate surroundings. Most of AGNs include several of the following components:

- A Supermassive black hole few AUs in diameter, having a mass in the following range: $10^6 < M_{BH} < 10^{10} M_{\odot}$.
- An accretion disk which is a sub-pc rotational dominated accretion flow, with a diameter of a few $R_{\odot}$. It radiates at optical, UV, EUV and X-ray wavelengths. The accretion disk can be optically thick or thin, and occasionally advection dominated.
- The Broad Line Region represented by high density, dust-free gas clouds moving at roughly Keplerian velocities up to $v \sim 10^4 km/s$ at a luminosity dependent distance of 0.01-1 pc from the BH.
- An axisymmetric dusty structure with dimensions of 0.1-10 pc, which obscures view on the AGN edge-on. This structure is called a torus and it radiates at IR wavelengths.
- The Narrow line region which is composed of ionised gas of lower density and velocity, extending from outside the torus to ~ 1 kpc along the in direction of the ionization cones.
- A thin molecular maser disk with sizes similar to those of the torus.
- A central radio jet with charged particles accelerated by magnetic fields and which produces synchrotron emission. The jets interact with ISM/IGM and can extend from several kpc to Mpc [41].

The class of AGNs of interest for this work are the radio-quiet, Type II Seyfert galaxies. These type of AGNs have quasar-like nuclei with very high surface brightness and their spectra reveal strong, high-ionization emission lines. Unlike quasars, the host galaxies of Seyferts, which are spiral or irregular galaxies, are detectable. The optical and IR spectra of Seyfert galaxies show very bright emission lines of H, He, N, O. The spectra of Type I Seyfert galaxies contain narrow lines associated with forbidden transitions, and broad lines associated with allowed strong dipole or inter-combination transitions, whereas the spectra of Type II Seyfert galaxies reveal only strong, narrow forbidden lines. These emission lines exhibit strong Doppler broadening, which implies high velocities spanning a range from 300 to 20000 km/s. These emission lines originate from the broad and narrow line regions surrounding the accretion disk of the central black hole. The classification in 2 types of Seyfert galaxies can be physically explained by the obscuration of the dusty torus with different orientation with respect to observers. Seyfert II galaxies are the Seyfert I galaxies observed edge on [41].

In this work, the distinction between star forming galaxies and AGNs is based on BPT (Baldwin, Phillips and Terlevich et al. 1981), as well as on WHAN (Cid Fernandes et al. 2011) diagnostic diagrams. These 2 methods use ratios of strong emission lines : $[OIII]/H\beta$ vs $[NII]/H\alpha$ and $EW_{H\alpha}$ vs $[NII]/H\alpha$ respectively, to distinguish whether the source of ionisation is of stellar origin or rather associated with AGN activity. For the comparison sample of field galaxies at higher redshifts, the Lamareille et al. 2010 diagnostic diagram ($[OII]/H\beta$ vs $[OIII]/H\beta$) is used, as at $z > 0.4$, the $[NII]$, and $H\alpha$ emission lines get redshifted out of the wavelength range of optical spectroscopic surveys, and bluer lines such as $[OII]$ need to be used instead.

5.2.1 BPT diagram for RXJ2248 cluster members

Using a set of 4 strong emission lines : $[OIII]$, $[NII]$, $H\alpha$, and $H\beta$ one can reliably distinguish between star-forming galaxies, Seyfert galaxies, low ionisation nuclear emission regions (LINERs) and composite galaxies with both star forming regions and an active galactic nucleus. This method, which allows to asses whether the source of ionisation is of pure stellar origin or rather associated with AGN activity, was first introduced by Baldwin, Phillips and Terlevich et al. 1981. Based on the BPT diagnostic, one is able to clearly distinguish between different classes of ionisation, by using strong, optical lines of close proximity in the ratios: $[NII]/H\alpha$ on the x axis and $[OIII]/H\beta$ on the y axis, limiting thus reddening and spectrophotometric effects. This emission line diagnostic diagram represents a major tool for the classification and analysis of emission-line galaxies. The extreme ultraviolet hard radiation field from the accretion disk of an AGN ionizes oxygen and nitrogen. Forbidden lines like $[NII]$ are only excited by high energy

photons, meaning that an AGN will generally have a higher ratio of $[NII]/H\alpha$ than a galaxy, whose highest energy photons are limited to those that can be produced by massive stars. This led to the conclusion the Seyfert II galaxies should have high values of each ratio $[NII]/H\alpha$ and $[OIII]/H\beta$ [42].

The work of Kewley and Dopita et. al 2002 provided a theoretical basis for the division between star forming galaxies and AGNs within BPT diagrams:

$$\log_{10}([OIII]/H\beta) = 0.61/([NII]/H\alpha - 0.47)) + 1.19 \quad (5.1)$$

with Type II Seyfert galaxies lying above this curve [43]. After this work, another differentiation between AGN and SF galaxies on the BPT diagram was developed by Kauffmann et al. 2003b, which is given by the empirical relation:

$$\log_{10}([OIII]/H\beta) = 0.61/([NII]/H\alpha - 0.05)) + 1.3 \quad (5.2)$$

If galaxies lie above the theoretical curve of Kewley et al. 2001 and empirical curve of Kauffmann et al. 2003 in the BPT diagram, with high values in both $[NII]/H\alpha$ and $[OIII]/H\beta$, then they can be classified as AGNs. If the galaxies lie above these two curves but have high values only in $[NII]/H\alpha$, then they are classified as LINERS. For galaxies that lie below the 2 borderline curves, the main source of ionisation comes from the stellar component, making them star forming galaxies. The area between these 2 curves represents the "uncertainty" region populated by composite galaxies with both active star formation and an AGN [44].

The BPT diagram was used for the RXJ2248 cluster members to separate star forming galaxies from Type II Seyferts, see fig. 5.5. From the cluster members with reliable measurements (quality flag $f=1$), two galaxies lie above the two separation curves, meaning that their main source of ionisation comes from an active SMBH. These two galaxies have the following IDs: 19720 at $z = 0.3441$ and 46905 at $z=0.3509$. Their spectra reveal very strong, narrow forbidden lines, see fig. 5.6. Other 2 galaxies described by a quality flag $f=1$ fall exactly on the theoretical curve of Kewley et al., with the error bars falling in the composite region of the diagram. These galaxies have the following IDs: 47559 and 17343 with $z = 0.3528$ and $z = 0.3490$ respectively. From the cluster galaxies described by a quality flag $f=2$, 5 fall in the AGN region, exceeding the two separation curves of the BPT diagram and one falls in the LINER region. The AGNs have the following IDs: 50661, 39624, 21643, 14744, 44418, whereas the LINER galaxy is 36059. As the dominant source of ionisation in these galaxies is of a non-stellar origin, they have been excluded from the sample of galaxies for the metallicity study.

Approximately 32 galaxies fall in the composite zone of the BPT diagram, thus meaning that their ISM is ionised by both the stellar component and a supermassive black hole.

BPT diagnostic diagram	f=1 RXJ2248 galaxies	f=2 RXJ2248 galaxies	f=3 RXJ2248 galaxies
nr. of AGNs	4	5	0
nr. of SF and composite galaxies	49	31	3

Table 5.1: This table shows the number of galaxies classified as AGNs/SF according to the BPT diagnostic diagram.

Table 5.1 summarises the main results of the BPT diagnostic diagram.

5.2.2 WHAN diagram for RXJ2248 cluster members

A second diagnostic diagram that separates star forming galaxies from AGNs was used for the RXJ2248 cluster members, as the BPT diagram can leave a fraction of emission line galaxies unclassified, due to quality requirements on the four emission lines. Cid Fernandes et al. 2010 proposed a more "economic" diagram, that allows one to attain the same objectives as the BPT diagram but, by using only two lines, $H\alpha$ and $[N II]$, which are in general the most prominent lines in the spectra of galaxies. However, this diagnostic diagram was proven to be less accurate than the BPT diagram.

The WHAN diagnostic diagram plots the equivalent width of the $H\alpha$ line on the y-axis versus the ratio $[NII]/H\alpha$ on the x-axis. This emission line diagnostic diagram should be used when encountering galaxy spectra with weak $[OIII]$ and $H\beta$ emission. The borderlines between different classes of galaxies were defined by optimal transpositions of the Kauffmann et al. (2003), Stasinska et al. (2006) and Kewley et al. (2006) borderlines on to the $EW_{H\alpha}$ versus $[NII]/H\alpha$ plane. The division into different ionisation classes is done as follows: Star-forming galaxies are defined as having a rest-frame $EW_{H\alpha} > 3\text{\AA}$, a $S/N_{H\alpha} > 5$ and $\log([NII]/H\alpha) \leq -0.3$, where as Type-2 Seyfert and LINERS are defined as having a rest-frame $EW_{H\alpha} > 3\text{\AA}$, a $S/N_{H\alpha} > 5$ and $\log([NII]/H\alpha) > -0.3$ [45].

The WHAN diagnostic diagram was used to distinguish between SF galaxies and AGNs in the RXJ2248 cluster, see fig. 5.7, and the results were compared to those offered by the BPT diagnostic. From the cluster galaxies which have a quality flag $f=1$ describing their spectra, 6 fall in the AGN region of the WHAN diagram. 4 of these galaxies also fall in the AGN region of the BPT diagram. The extra 2 galaxies classified as AGNs according to the WHAN diagram are: 27355 and 53910 at $z = 0.3346$ and $z = 0.3522$ respectively. From the cluster members which have a quality flag $f=2$ describing their spectra, 16 were classified as AGNs. 6 of them were also classified as AGNs according to the BPT diagram. The other 10 galaxies which fall in

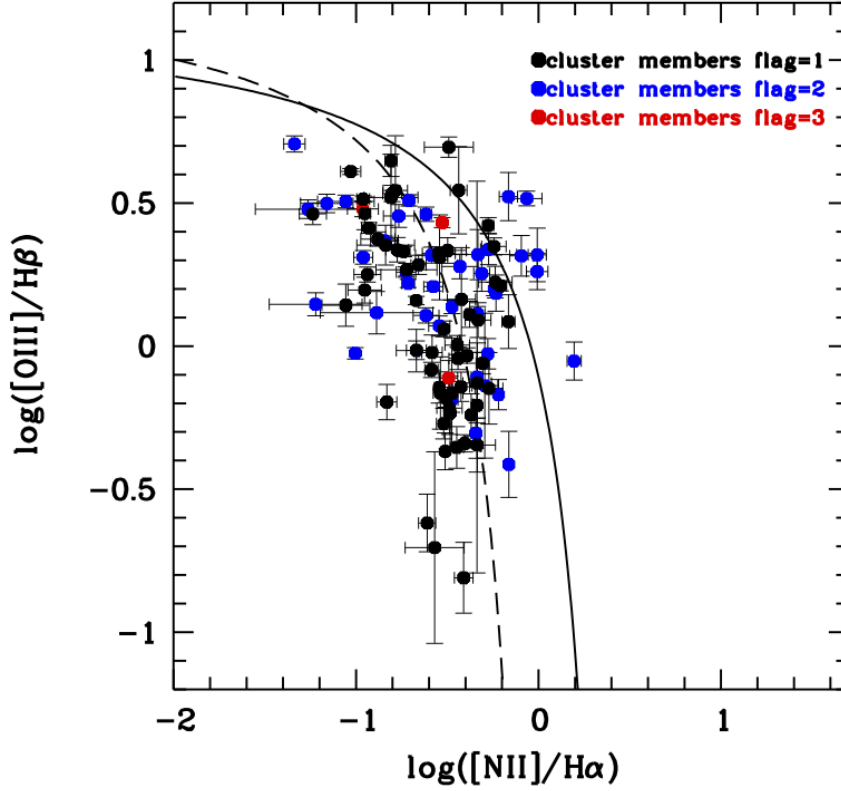


Figure 5.5: BPT (Baldwin et al. 1981) diagram for the RXJ2248 cluster members. This diagnostic diagram is used to distinguish whether the dominant source of ionisation comes from the stellar component or from an AGN. The solid curve represents the theoretical curve of Kewley et al. 2001 and the dashed one represents the empirical curve of Kauffmann et al. 2003, which separate star-forming galaxies (below/left of the curves) from AGNs (above/right of the curves). The colour code stands for the different quality flags assigned to the spectra. The vertical and horizontal lines surrounding each point represent the error bars.

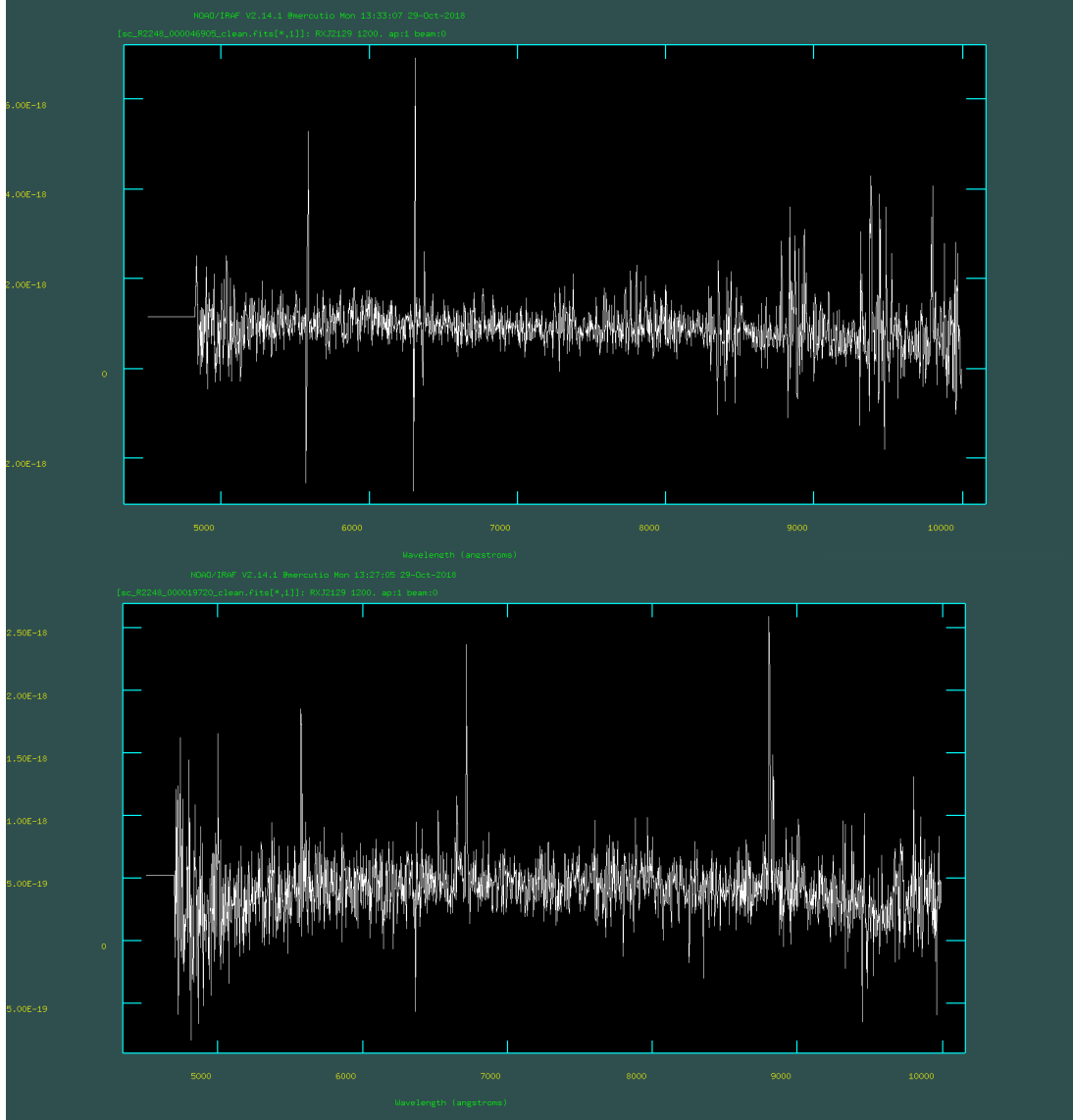


Figure 5.6: Spectrum of RXJ2248 cluster galaxy 46905 (top) and 19720 (bottom), which were classified as AGNs according to the BPT diagnostic diagram. These spectra show strong narrow forbidden emission lines.

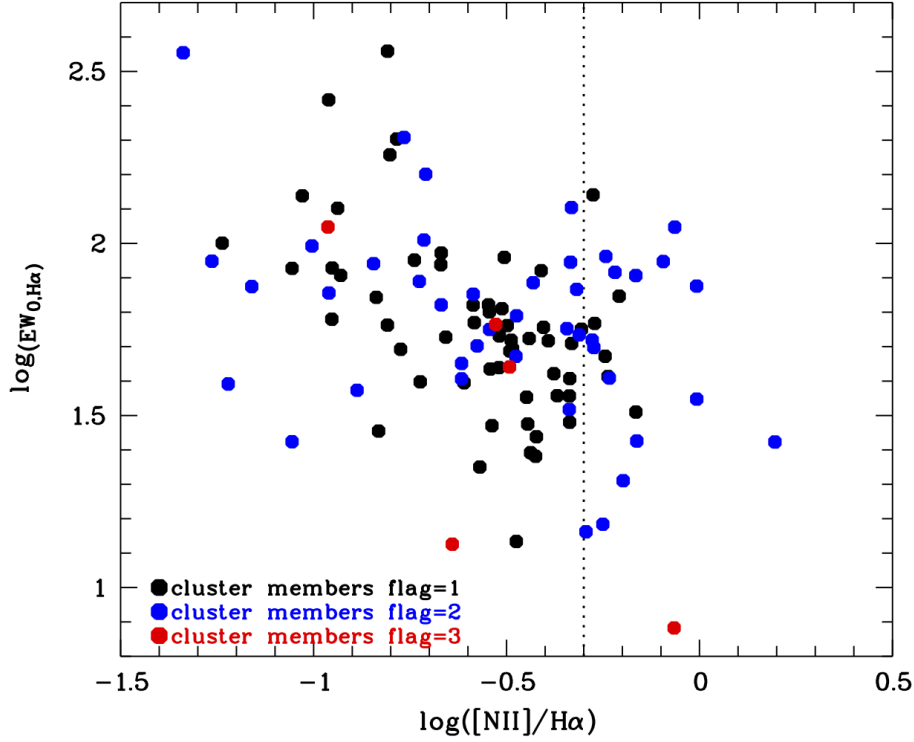


Figure 5.7: WHAN (Cid Fernandes et al. 2011) diagram for RXJ2248 cluster members. This diagnostic diagram is used in order to distinguish whether the dominant source of ionisation comes from the stellar component or from an AGN. The dashed line represents the separation between star forming galaxies (left) and Type II Seyfert or LINERS (right). The colour code stands for the different quality flags assigned to the spectra.

the Type II Seyfert/LINERS zone are: 40486, 16334, 42109, 49541, 47707, 36059, 35131, 33812, 19985 and 16387.

In order to accurately derive gas-phase metallicities for the investigated cluster galaxies, the objects classified as AGNs by the BPT diagram were excluded from the sample. The extra objects classified as AGNs by the WHAN diagram were treated more carefully in the metallicity study, as they also fall in the composite region of the BPT diagram.

Table 5.2 summarises the main results according to the WHAN diagnostic diagram.

5.2.3 SF galaxies and Type II AGNs in the field population

As mentioned earlier, the sample of field galaxies was subdivided into 2 redshift bins: $0.01 < z < 0.33$ (low redshift bin), $0.33 < z < 0.36$ (galaxies from the field of the MACSJ0416, middle redshift bin) and $0.36 < z < 0.9$ (high redshift bin). For galaxies with $z < 0.36$, the distinction

WHAN diagnostic diagram	f=1 RXJ2248 galaxies	f=2 RXJ2248 galaxies	f=3 RXJ2248 galaxies
nr. of AGNs	6	16	1
nr. of SF and composite galaxies	47	20	4

Table 5.2: This table shows the number of galaxies classified as AGNs/SF according to the WHAN diagnostic diagram.

between SF galaxies and AGNs is based on classical BPT diagrams, see fig. 5.8 and 5.9.

According to this diagnostic diagram, 9 out of 145 galaxies from the low redshift bin can be classified as AGNs. From the sample of 7 galaxies with $0.33 < z < 0.36$, none fall in the AGN region of the BPT diagram. However, 2 of these 6 galaxies are located in the composite region of the BPT diagram, meaning that their ISM is ionised by both a stellar component and an AGN.

At redshifts greater than $z \sim 0.4$, the [NII], and $H\alpha$ emission lines get redshifted out of the wavelength range of optical spectroscopic surveys, and BPT diagnostic diagrams can not be used anymore. Therefore, the distinction between SF galaxies and AGNs will be based on emission lines observed in the blue part of the spectrum: [OIII], [OII], and $H\beta$. A diagnostic diagram that uses only bluer emission lines was devised by Lamareille et al. 2010. It plots on the x axis the ratio $[OII]/H\beta$ and on the y-axis the ratio $[OIII]/H\beta$. The separation between star forming galaxies and Seyfert/LINERS is given by the following equation:

$$\log([OIII]/H\beta) = \frac{0.11}{\log([OIII]/H\beta) - 0.92} + 0.85 \quad (5.3)$$

Galaxies located above this curve, with both high values of $[OII]/H\beta$ and $[OIII]/H\beta$ will be classified as Type II Seyfert galaxies. LINERs are also located above this theoretical curve, but at lower values of $[OIII]/H\beta$. Star forming and composite AGN/SF galaxies will be located below the curve [46]. Fig. 5.10 shows such a diagnostic diagram for the field galaxies from the high redshift bin.

Based on this diagram, just 1 out of 173 galaxies can be securely classified as an AGN, with another 2 galaxies falling in the uncertainty region, exceeding the separation curve of Lamareille. All the field galaxies classified as AGNs according to BPT/Lamareille diagnostic diagrams were excluded from the metallicity study. Field galaxies which fall in the uncertainty regions of both these diagrams were also excluded from the comparison sample.

Table 5.3 summarises the main results of this section.

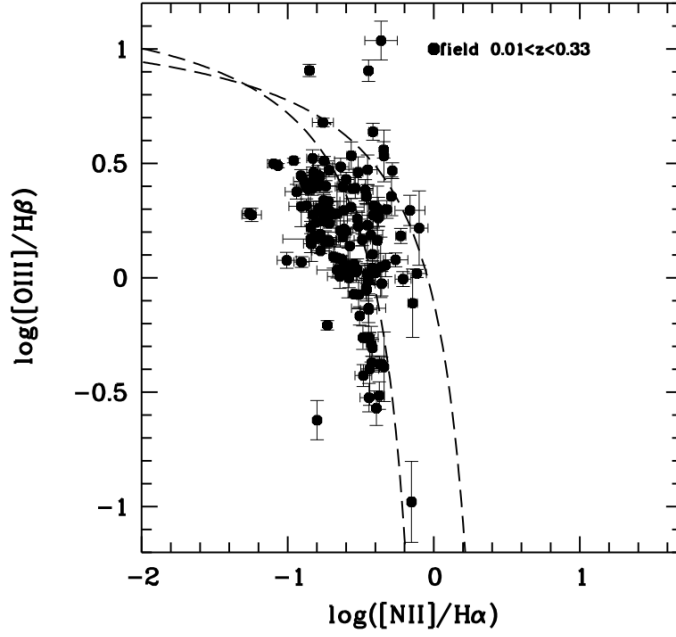


Figure 5.8: BPT (Baldwin et al. 1981) diagram for the field galaxies from the low redshift bin ($0.01 < z < 0.36$). The solid curve represents the theoretical curve of Kewley et al. 2001 and the dashed one represents the empirical curve of Kauffmann et al. 2003, which separate star-forming galaxies (below/left of the curves) from galaxies whose main source of ionisation comes from an AGN (above/right of the curves).

BPT/Lamareille diagnostic diagram	field galaxies low z bin	field galaxies middle z bin	field galaxies high z bin
nr. of AGNs	9	0	3
nr. of SF and composite galaxies	136	7	141

Table 5.3: This table shows the number of galaxies classified as AGNs/SF according to the WHAN diagnostic diagram.

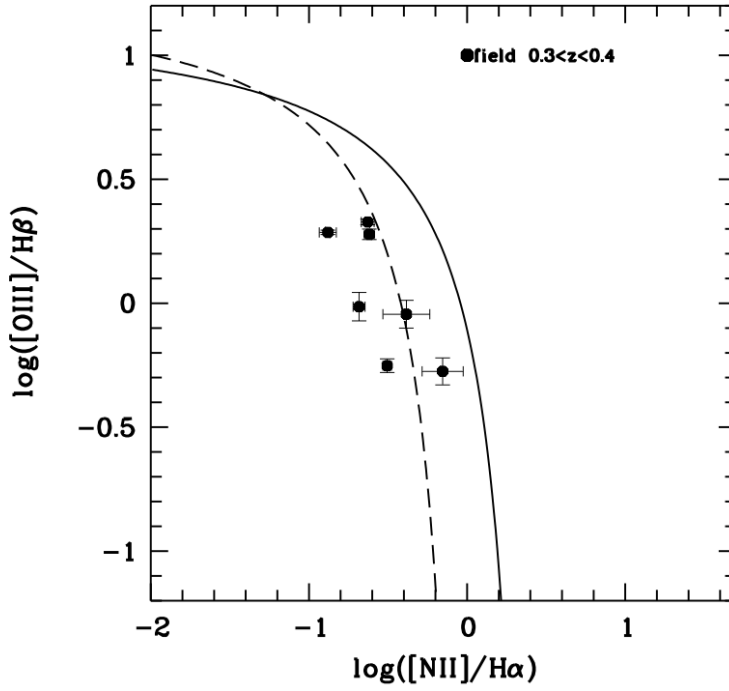


Figure 5.9: BPT (Baldwin et al. 1981) diagram for the field galaxies from the middle redshift bin ($0.33 < z < 0.36$). The solid curve represents the theoretical curve of Kewley et al. 2001 and the dashed one represents the empirical curve of Kauffmann et al. 2003, which separate star - forming galaxies (below/left of the curves) from galaxies whose main source of ionisation comes from an AGN (above/right of the curves).

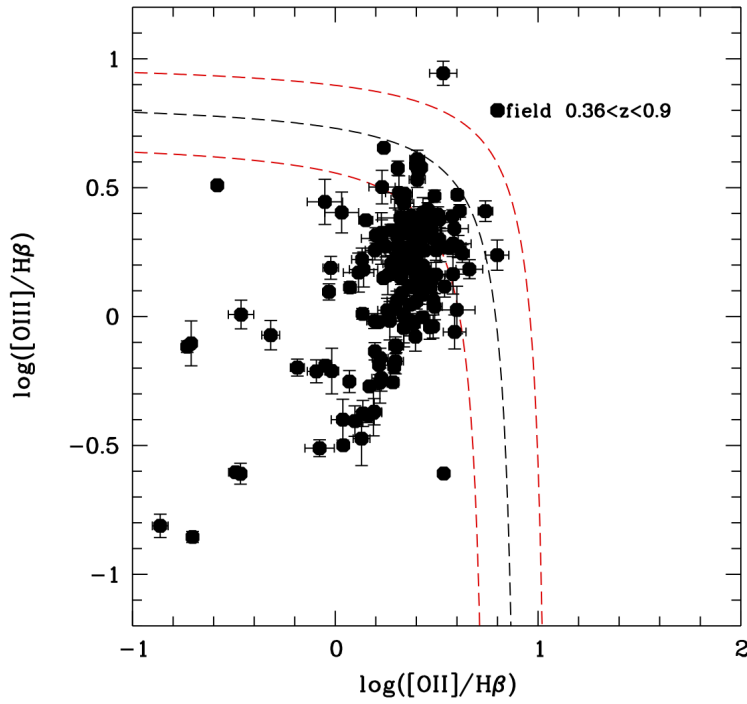


Figure 5.10: Lamareille et al. 2010 diagnostic diagram for the field galaxies from the high redshift bin ($0.36 < z < 0.94$). The black, dotted curve makes the distinction between star-forming galaxies (below/left of the curves) and galaxies whose main source of ionisation comes from an AGN (above/right of the curves). The 2 red, dotted lines give the uncertainty region.

5.3 Stellar Mass - Star Formation Rate relation

The galaxy stellar mass - star formation rate relationship offers key constraints on the histories of the stellar mass buildup of galaxies. Parameters governing the star formation activity offer an insight into the evolution of galaxies, whereas the cosmic evolution of SFRs provides information about the mass assembly of galaxies and subsequently about the development of the Hubble sequence.

In the Λ CDM cosmological model, it is believed that gas is gravitationally accreted into dark matter halos, decoupling from the non-baryonic matter due to radiative processes to settle into a star-forming disk. If a molecular gas cloud is cold and massive enough, so that the gas pressure is insufficient to support it, then it will undergo gravitational collapse. The mass above which a cloud will become gravitationally unstable and collapse is called the Jeans Mass:

$$M_J = \left(\frac{\pi}{6}\right)\rho \cdot R_J = \frac{(c_s)^3}{G^{3/2}\rho^{1/2}} \quad (5.4)$$

where R_J is the Jeans length, c_s the sound speed, and ρ the density[47].

Calibrations of SFR indicators, based on both continuum and line emission, have been derived across the whole electromagnetic spectrum, from X-rays to the radio wavelengths. The relation of a galaxies mass and its SFR is thus an important indicator of the contribution of recent star formation to the buildup of the total stellar mass of a galaxy. For galaxies with ongoing star formation and $z \leq 2$, the $M_* - SFR$ relation was observed to be a pretty tight with a slope just below unity with a scatter of ~ 0.3 dex. The sSFR-M relation evolves downwards in amplitude with decreasing redshift, suggesting that a global quenching mechanism is responsible for the decrease in the SFR.[48].

5.3.1 Derivation of SFRs

The $H\alpha$ emission line is one of the most reliable and best-understood SFR indicators. Only the most massive stars with masses $> 10M_\odot$ and lifetimes $< 20Myrs$ have a significant contribution to the ionizing flux, so the emission lines, which re-emit this luminosity, provide us with an instantaneous estimate of the SFR, independent of the previous star formation history. The $H\alpha$ nebular emission arises directly from the recombination of HII gas ionized by the most massive O- and early B-type stars and therefore traces the star formation over the lifetimes of these stars. The luminosity of the $H\alpha$ recombination line is directly coupled to the incident number of $Ly\alpha$ photons produced by these young stars, and is hence proportional to the SFR. However, since the ionizing flux comes only from the most massive stars, in order to get the total SFR one

has to extrapolate to lower masses using the Initial Mass Function (IMF). The luminosity of the $H\alpha$ line, as well as the broadband colours of galaxies, are known to be very sensitive to the slope of the IMF. Because of this, they can be used to constrain the IMF slope. The Salpeter IMF was proven to fit the properties of normal spiral galaxies better than other IMFs and should be therefore the adopted IMF when deriving SFRs from nebular emission lines.

The luminosity of the $H\alpha$ emission line can be therefor used to calculate the SFR, by applying the Kennicutt (1998) conversion [49]:

$$SFR(M_{\odot} \cdot yr^{-1}) = 7.9 \cdot 10^{-42} L(H\alpha)(ergs/s) \quad (5.5)$$

The intensities of emission lines arising from gas nebulae are strongly affected by selectively absorbing material on the line of sight to the observer. Thus, the most important source of systematic error in $H\alpha$ -derived SFRs is the extinction induced by dust. In order to properly estimate SFRs based on the luminosity of the $H\alpha$ line, the extinction in $H\alpha/H\beta$ is needed. The intrinsic $H\alpha/H\beta$ line ratio is insensitive to the density and to the electron temperature but is however affected by dust. By assuming a Balmer recombination with a temperature of $T=10,000$ K and a density of $\rho = 100 cm^{-3}$, then $H\alpha/H\beta = 2.86$. Observed $H\alpha/H\beta > 2.86$ indicates extinction, and the $H\alpha$ flux has to be corrected accordingly [50]. The de-reddened value for a emission line ratio $I(\lambda_1)/I(\lambda_2)$, is given by the following expression, according to Brocklehurst et al. 1971 :

$$\frac{I(\lambda_1)}{I(\lambda_2)} = \frac{F(\lambda_1)}{F(\lambda_2)} \cdot 10^{c[f(\lambda_1)-f(\lambda_2)]} \quad (5.6)$$

where $F(\lambda)$ is the observed flux at a given wavelength, c is the logarithmic reddening parameter that describes the amount of reddening relative to $H\beta$, and $f(\lambda)$ is the wavelength-dependent reddening function cite51. One can approximate a value for the function $f(\lambda)$ over the whole spectral range using the following expression, according to Izotov et al. 1994:

$$f(\lambda) = 3.15854 \cdot 10^{-1.02109\lambda} - 1 \quad (5.7)$$

where λ is measured in μm [52]. For the $H\alpha$ line, we have: $\lambda_{H\alpha} = 0.6563 \mu m$, $f(\lambda) = -0.325$. The effect of reddening on the $H\alpha/H\beta$ emission line ratio can be expressed as:

$$\frac{I(H\alpha)}{I(H\beta)} = \frac{F(H\alpha)}{F(H\beta)} \cdot 10^{-0.332c} \quad (5.8)$$

Knowing that the intrinsic $H\alpha/H\beta$ ratio is ~ 2.86 , equation 5.8 can be rewritten as:

$$F(H\alpha) = 2.86 \cdot F(H\beta) \cdot 10^{0.332c} \quad (5.9)$$

The logarithmic reddening parameter c is given by the following equation:

$$c = 1.47 \cdot E_{B-V} = 1.47 \cdot A_V/3.2 = 0.46 \cdot A_V \quad (5.10)$$

where E_{B-V} stands for the colour excess and A_V for the extinction parameter. By substituting c in equation 5.9 one obtains:

$$F(H\alpha) = 2.86 \cdot F(H\beta) \cdot 10^{0.152A_V} \quad (5.11)$$

The above equation can be rewritten as:

$$A_V = 6.547 \cdot \log_{10}\left(\frac{F(H\alpha)}{2.86 \cdot F(H\beta)}\right) \quad (5.12)$$

offering an expression for the extinction parameter. The de-reddened flux of an observed emission line is given by the following expression, according to Seaton et al. 1979 [53]:

$$F_{der} = F_{obs} \cdot 10^{0.46A_V \cdot (1+f(\lambda))} \quad (5.13)$$

By substituting equation 5.12 and the value for $f(\lambda)$ in equation 5.13, one obtains the following expression for the de-reddened $H\alpha$ flux:

$$F(H\alpha)_{der} = F(H\alpha)_{obs} \cdot 10^{2.03 \cdot \log_{10}\left(\frac{F(H\alpha)}{2.86 \cdot F(H\beta)}\right)} \quad (5.14)$$

In order to compute the luminosity of the $H\alpha$ line, the luminosity distance to the investigated galaxies is needed. The luminosity distance was computed by means of a python code, using the *astropy.cosmology* package of *astropy*. The used cosmological parameters are in accordance to the Λ CDM model: $H_0 = 70 \text{ km Mpc}^{-1} \text{ s}^{-1}$, $\Omega_{m,0} = 0.27$, $\Omega_{\Lambda,0} = 0.73$. Under the assumption of spherical symmetry, and by knowing the luminosity distance to the investigated galaxy, the luminosity of $H\alpha$ emission line can be calculated as follows:

$$L(H\alpha) = 4\pi \cdot D_L^2 \cdot F(H\alpha)_{der} \quad (5.15)$$

Thus, the SFR can be derived by applying the following conversion:

$$SFR(M_\odot \cdot \text{yr}^{-1}) = 7.9 \cdot 10^{-42} \cdot 4\pi \cdot D_L^2 (\text{Mpc}^2) \cdot F(H\alpha)_{der} (10^{-17} \text{ ergs s}^{-1} \text{ cm}^{-2}) \quad (5.16)$$

By converting to SI units, equation 5.16 will have the following form:

$$SFR(M_\odot \cdot \text{yr}^{-1}) = 9.45 \cdot 10^{-9} \cdot D_L^2 \cdot F(H\alpha)_{der} (\text{erg/s}) \quad (5.17)$$

As the slits of the VIMOS masks have a width of 1 arcsec, some of the emission from the galaxy will get lost. Therefore, an aperture correction needs to be applied to the $H\alpha$ line flux in order to compute accurate SFRs. Without this correction, the calculated SFRs will be too low. For the computation of the slit loss correction, we have used the ESO-MIDAS software. The first step requires to convolve each CLASH-VLT VIMOS spectrum with the WFI R filter. For this purpose, a table containing the wavelength and transmission of the WFI R band was used (the

same table as provided by LePhare). Then, by using the ESO-Midas procedure *comp/ima*, a product was compiled for the transmission function of the filter and the VIMOS spectra.

The monochromatic AB magnitude is important to understand how the slit loss correction works.

The AB magnitude is based on flux measurements that are calibrated in absolute units:

$$m_{AB} = -\frac{5}{2} \cdot \log(f_\nu) - 48.6 \quad (5.18)$$

with

$$f_\nu = \frac{\lambda^2}{c} \cdot f_\lambda \quad (5.19)$$

f_ν stands for the spectral flux density per unit frequency where as f_λ stands for the spectral flux density per unit wavelength [54]. f_ν can also be expressed as follows:

$$f_\nu = \frac{\int_0^\infty S(\lambda) \cdot T(\lambda) d\lambda}{\int_0^\infty T(\lambda) d\lambda} \quad (5.20)$$

where $S(\lambda)$ is the transmission-function of the spectrum and $T(\lambda)$ is the transmission function of the filter [55]. In order to solve equation 5.20, the ESO-Midas procedure *sta/image* is applied on the image with the transmission function of the filter and on the image of the product between the transmission function of the filter and the spectrum. When the procedure *sta/image* is applied to the image of the transmission function of the filter, one obtains a mean value which corresponds to $f_{\lambda, filter}$. When the same procedure is applied for the product between the transmission function of the filter and the spectrum, the software offers a mean value which corresponds to $f_{\lambda, spectrum}$. Then, the values for these two quantities are used in equation 5.19 as follows:

$$f_\nu = \left(\frac{f_{\lambda, spectrum}}{f_{\lambda, filter}} \cdot \frac{\lambda_{mean, R-filter}^2}{c} \right) \quad (5.21)$$

where $\lambda_{mean, R-filter} = 6517 \text{ \AA}$ and the speed of light $c = 3 \cdot 10^{18} \text{ \AA/s}$. Then, the computed value for f_ν is substituted in equation 5.18 and one obtains a value for the AB magnitude in R-band.

As last, the slit loss correction is given by the following equation:

$$corr - slitloss = 10^{0.4 \cdot (m_{AB} - m_R)} \quad (5.22)$$

where m_R stands for the observed magnitude in R-band.

For $\sim 90\%$ of the sample, the aperture correction factors have values between 1 and 3. This correction assumes that both the $H\beta$ line flux and R-band continuum were equally affected by the slit losses.

The SFRs are then corrected for these aperture effects as follows:

$$SFR(M_\odot \cdot yr^{-1}) = 9.45 \cdot 10^{-9} \cdot D_L^2 \cdot F(H\alpha)_{der} \cdot corr - slitloss(erg/s) \quad (5.23)$$

The main advantages of this calibration are its high sensitivity, and the direct proportionality between the luminosity of the nebular emission and the SFR. Even with small telescopes, the star formation can be mapped at high resolution in nearby galaxies, and the $H\alpha$ emission line remains detectable in the redshifted spectra of starburst galaxies up to $z > 2$. However, this method has some limitations, such as its sensitivity to uncertainties in extinction and the IMF, and the assumption that all massive star formation is traced by the ionized gas [49].

As most of the field galaxies from the high-redshift bin do not have measurements of the $H\alpha$ emission line flux, because this line is redshifted into the NIR, their SFRs have to be determined using bluer emission lines. One of the most prominent emission features in the blue part of the spectrum is the $[OII]\lambda 3727$ forbidden-line. The luminosity of the $[OII]$ emission line is however less directly coupled to the ionising flux produced young stars than the $H\alpha$ line, and suffers larger uncertainties as an SFR indicator, as it is more sensitive to dust and metallicity. The excitation of $[OII]$ line is however sufficiently well behaved in order to be calibrated empirically as a quantitative SFR tracer. The calibration by Gilbank et al. 2010 was used in order to determine the SFRs for these sample of field galaxies at redshifts $z > 0.36$ [56]. This SFR indicator which uses the luminosity of the $[OII]$ line is based on the calibration by Kennicutt et al. 1998, which derived a scaling between the $[OII]$ and $H\alpha$ luminosity as:

$$\frac{SFR_0}{M/M_\odot \cdot yr^{-1}} = \frac{L([OII])}{3.80 \cdot 10^{40}} (erg/s) \quad (5.24)$$

This original scaling, derived by Kennicutt et al. originated from the $H\alpha$ SFR calibration and the normalisation constant considers theoretical values for the $H\alpha/[OII]$ luminosity and for the extinction [49]. Gilbank et al. 2010 derived an empiric correction for the calibration mentioned above:

$$SFR_{emp,corr} = \frac{SFR_0}{a \cdot \tanh\left(\frac{(x-b)}{c}\right) + d} \quad (5.25)$$

where $x = \log(M/M_\odot)$ and $a = -1.424$, $b = 9.827$, $c = 0.572$ and $d = 1.700$ [56].

After the unit conversion, equation 5.25 will have the following form:

$$SFR_{emp,corr}(M_\odot \cdot yr^{-1}) = \frac{4.73 \cdot 10^{-8} \cdot D_L^2 \cdot F([OII])}{-1.424 \cdot \tanh((\log(M/M_\odot) - 9.827)/0.572) + 1.7} (erg/s) \quad (5.26)$$

After applying the slit-loss correction, the SFR based on the luminosity of the $[OII]$ emission line will be calculated as follows:

$$SFR_{emp,corr}(M_\odot \cdot yr^{-1}) = \frac{4.73 \cdot 10^{-8} \cdot D_L^2 \cdot F([OII])}{-1.424 \cdot \tanh((\log(M/M_\odot) - 9.827)/0.572) + 1.7} \cdot corr-slitloss (erg/s) \quad (5.27)$$

A disadvantage of the $[OII]$ -derived SFRs is, that it may be prone to systematic errors from extinction and variations in the diffuse gas fraction. The excitation of $[OII]$ is especially high in

the diffuse ionized gas in starburst galaxies.

The sSFR-M relation is an important indicator of the contribution of recent star formation to the buildup of the total galaxy mass, and in order to compute this relation, the specific star formation rate is required. The sSFR is defined as the star formation rate per unit stellar mass:

$$sSFR = \frac{SFR}{M_*} \quad (5.28)$$

The inverse of the sSFR gives us a measure of the characteristic time scale for the build-up of the total stellar mass:

$$\tau_{SFR} = \frac{1}{sSFR} \quad (5.29)$$

τ_{SFR} reflects the time needed for the galaxy to form all its stellar mass at the current SFR, thus offering an insight into the star formation history of the system. If $\tau_{SFR} > \text{age of the universe}$, then we are dealing with a quiescent galaxy which is currently not forming stars any more, meaning that its SFR should have been higher in the past. However, if $\tau_{SFR} < \text{age of the universe}$, then the galaxy in question is still actively forming stars, but its SFR could not have been that high over the whole life time of the system. The sSFRs have been computed for the whole sample of RXJ2248 cluster and field galaxies with available measurements of the $H\alpha$ and [OII] emission lines.

5.3.2 sSFR-Mass relation for RXJ2248 cluster members

The star formation rate mass relation was first studied by K. G. Noeske et al. 2007 for a sample of galaxies in the Aegis field with redshifts between $0.2 < z < 1.1$. They find that the galaxies, which show reliable signs of SF form an apparent sequence, with a limited range of SFR values at a given stellar mass and redshift (a scatter of $\sigma < 0.35$ dex) and with the $\log(SFR) \propto M_*$. This correlation between SF and stellar mass was defined as the "main sequence of star forming galaxies" [48].

Fig. 5.11 shows the sSFR-M relation for the RXJ2248 cluster galaxies. The plot from the left-hand side shows the specific star formation rate as a function of the stellar masses for all RXJ2248 cluster members which have flux measurements of the $H\alpha$ line. The colour codes stand for the different quality flags assigned to the spectra: black, blue and red represent galaxies which are described by quality flags $f=1$, $f=2$, and $f=3$ respectively. The black cross in the upper left corner shows the mean error in the derivation of the SFR and stellar mass. The red solid line represents the main sequence of star forming galaxies for a redshift of $z \sim 0.4$, as determined by Peng et al. 2010. The authors of this paper derived an equation for the evolution of the sSFR as a function of mass and time based on a purely empirical, observational approach. By

linking together the sSFR at $z \sim 2$ and $z \sim 1$ of Daddi et al. 2007a and Elbaz et al. 2007 with zCOSMOS and SDSS data, Peng et. al 2010 derived the following equation for the main sequence of SF galaxies at a given redshift [57]:

$$sSFR(M, t) = \frac{1}{\tau_{SFR}(M, t)} = 2.5 \cdot \left(\frac{M}{10^{10} M_{\odot}}\right)^{\beta} \cdot \left(\frac{t}{3.5 Gyr}\right)^{-2.2} Gyr^{-1} \quad (5.30)$$

For a redshift of $z \sim 0.4$, the above equation can be rewritten as:

$$\log(sSFR) = -0.24 \cdot \log(M) + 1.86 \quad (5.31)$$

Equation 5.31 was used to derive the MS of SF galaxies for the RXJ2248 cluster, and is represented in fig. 5.11 by the red solid line. The red dotted lines represent the 0.3 dex dispersion of this relation. We have assumed a dependence of sSFR on mass as it was observed for SDSS galaxies in the local universe by Peng et. al 2015 [58]:

$$sSFR \propto m_{star}^{\beta} \text{ with } \beta \sim -0.24 \quad (5.32)$$

The panel on the right-hand side plots the sSFR-M relation only for the cluster members described by a quality flag $f=1$, as they have accurate measurements of the emission lines of interest. The black points represent the galaxies described by a quality flag $f=1$, and the red points represent the cluster AGNs, as identified by the BPT diagnostic diagram. The green open diamonds show the median values of the sSFR in 2 mass bins: $8.3 < \log(M/M_{\odot}) < 9.5$ (low M bin) and $9.5 < \log(M/M_{\odot}) < 11$ (high M bin). The black cross from the upper left corner stands for the mean error in the estimation of the sSFR and of the stellar mass. The solid and dotted red lines represent the main sequence of SF galaxies at a redshift of $z \sim 0.4$ together with its scatter. If galaxies lie ± 0.3 dex around the red solid line, then they can be classified as star forming main sequence galaxies. The galaxies located below the red line represent the quiescent, passive population, which shows little to no ongoing star formation. If galaxies lie above the red solid line, then these systems can be classified as starburst galaxies.

Fig. 5.12 shows the offset of the sSFRs of cluster members to the main sequence of star forming galaxies at a redshift of $z \sim 0.4$. The diagram on the left-hand side shows $\Delta sSFR$ to the MS value at a given mass as a function of the stellar masses for all cluster members which have measurements of the $H\alpha$ emission line. The colour codes represent the different quality flags assigned to the spectra and are the same as in the previous plots. The panel on the right-hand side shows the offset to the MS of SF galaxies at $z \sim 0.4$ as well, but only for the galaxies described by a quality flag $f=1$, which are represented by the black dots. The red dots show the location of the cluster AGNs in the $\Delta sSFR - M$ plane, whose SFRs are not reliable, as the Kenicutt et al. conversion only works for galaxies, whose main source of ionisation comes from

a stellar origin. The green open diamonds show the median values of the offset of the SFRs of cluster galaxies to the MS of SF galaxies for the two aforementioned mass bins.

The mean values for the sSFRs and the scatter of the data points are quite consistent with the MS relation and with the scatter predicted by Peng et al. (2010) at $z \sim 0.4$. The mean values of the SFR in both the low and high mass bin is ~ -0.39 for the cluster galaxies described by a quality flag $f=1$. The median $\Delta sSFR$ has a value of ~ -0.07 in the low mass bin, and a value of ~ 0.162 in the high mass bin, meaning that most of the RXJ2248 cluster members, which are described by a quality flag $f=1$, can be classified as MS SF galaxies. In the low mass end ($\log(M/M_\odot) < 9.5$), we have, besides the $f=1$ MS galaxies, 4 quiescent galaxies showing $\log(sSFR/Gyr^{-1}) < -1$, lying far below the MS, and 4 galaxies with enhanced SFRs, lying above the MS. At the high mass end ($\log(M/M_\odot) > 9.5$), we have in addition to the MS galaxies, 1 passive system and 4 lying above the MS. By taking in account the typical errors of $\sim \pm 0.03$ dex of the SFR estimation, ~ 46 RXJ2248 cluster members described by a quality flag $f=1$ can be classified as MS SF galaxies, 5 as quiescent galaxies, and 8 as starburst galaxies.

5.3.3 sSFR-Mass relation for the comparison field sample

Fig. 5.13 shows the specific star formation rate - mass relation for the sample of field galaxies. The panel from the left-hand side plots the sSFR as a function of the stellar mass for the low redshift sample of field galaxies, which have available flux measurements of the $H\alpha$ emission line. The black points represent the galaxies described by a quality flag $f=1$, whereas the red points represent the Seyferts II, as identified by the BPT diagnostic diagram, which do not have reliable sSFRs. The red solid line represents the main sequence of star forming galaxies for a redshift of $z \sim 0.2$, as derived by Peng et al. 2010, using the following equation [57]:

$$\log(sSFR) = -0.24 \cdot \log(M) + 1.7 \quad (5.33)$$

The red dotted lines represent the 0.3 dex dispersion of this relation.

The plot on the right-hand side shows sSFR-M relation for the sample of field galaxies from the high redshift bin, which have available measurements of the [OII] line. Only $f=1$ field galaxies are shown in this plot in black, together with the AGNs, as classified by the Lamareille et. al 2010 diagnostic diagram, in red. The solid and dotted lines represent the main sequence of SF galaxies at a redshift of $z \sim 0.5$ with its scatter, as derived by Peng et. al 2010 using the following equation[57]:

$$\log(sSFR) = -0.24 \cdot \log(M) + 1.948 \quad (5.34)$$

Galaxies which lie ± 0.3 dex around the red solid line will be classified as main sequence, star

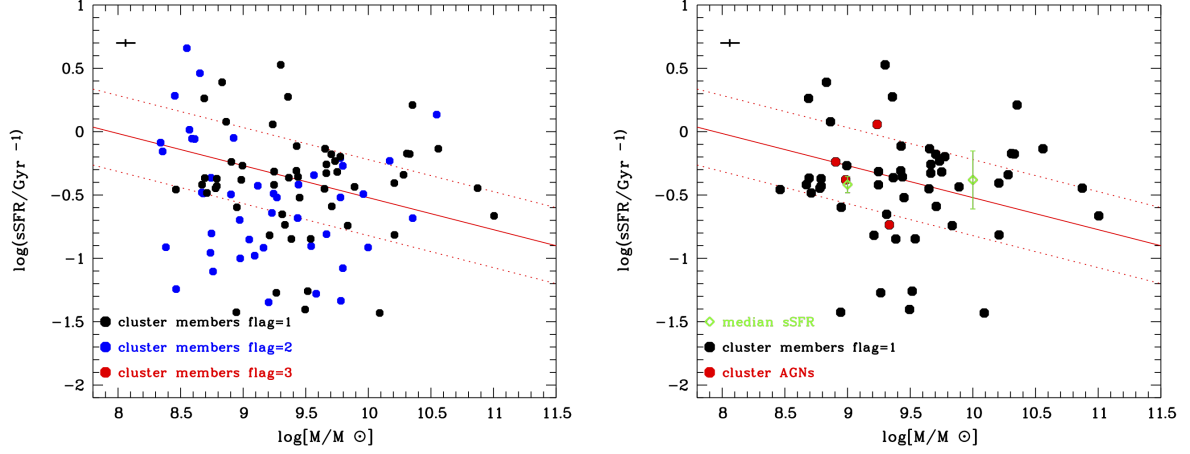


Figure 5.11: sSFR-M relation for the RXJ2248 cluster members. The panel on the left-hand side plots the specific star formation rate as a function of the stellar mass for all RXJ2248 cluster members with available measurements of the $H\alpha$ emission line. The colour codes represent the different quality flags assigned to the spectra: black, blue and red stand for the quality flags $f=1$, $f=2$, and $f=3$ respectively. The plot on the right-hand side shows the sSFR-M relation only for the cluster galaxies with accurate measurements of the emission lines of interest, which were selected for the metallicity study, and points out the AGNs in red, for which we have no reliable sSFR estimate. The green open diamonds stand for the median value for the sSFRs of cluster galaxies. The black cross in the upper left corner of both diagrams represents the mean error of the sSFR and M estimation. The red solid line in both panels represents the main sequence of star forming galaxies for a redshift of $z \sim 0.4$ as derived by Peng et al. 2010. The dashed red lines represent the 0.3 dex dispersion of the MS. If galaxies lie ± 0.3 dex around the red solid line, then these systems belong to the star forming main sequence.

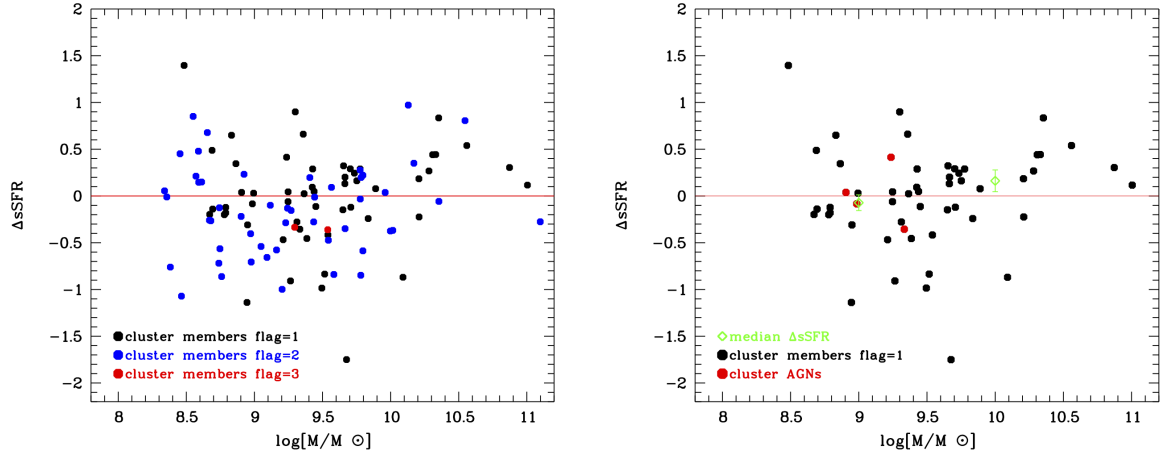


Figure 5.12: Median offset of the sSFRs of RXJ2248 cluster members to the main sequence of star forming galaxies at a redshift of $z \sim 0.4$. The panel on the left-hand side plots $\Delta sSFR$ as a function of the stellar masses for all cluster members which have measurements of the $H\alpha$ emission line. The colour codes stand for the different quality flags assigned to the spectra. The panel on the right-hand side also shows the offset to the MS of SF galaxies at $z \sim 0.4$ but only for the galaxies described by a quality flag $f=1$, which are represented by the black dots. The red dots show the location of the cluster AGNs in the $\Delta sSFR - M$ plane, which do not have reliable SFRs. The green diamonds stand for the median value of $\Delta sSFR$ for cluster galaxies.

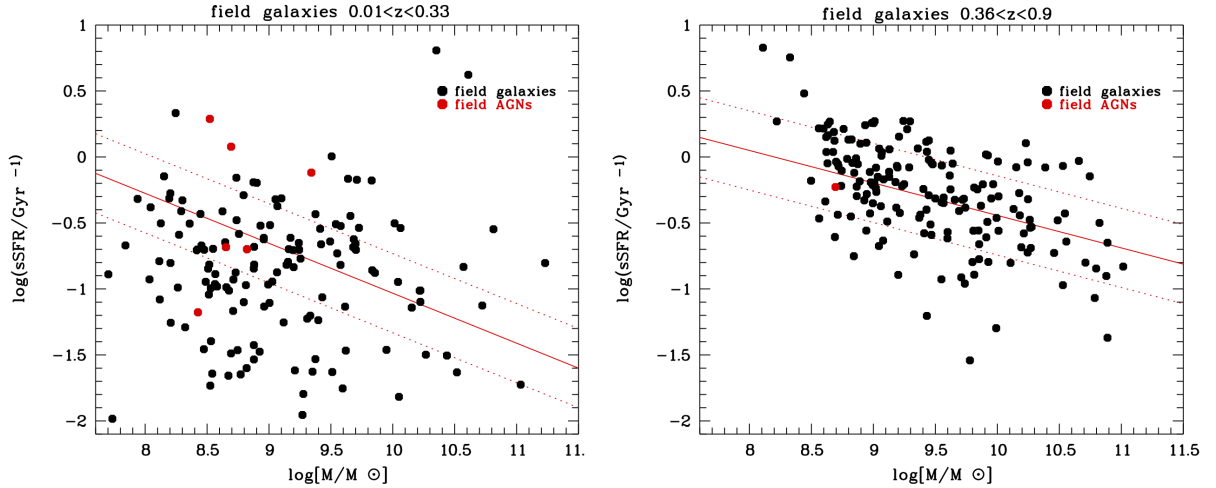


Figure 5.13: sSFR-M relation for the field galaxies. The panel on the left-hand side plots the specific star formation rate as a function of the stellar mass for the sample of field galaxies from the low redshift bin ($0.01 < z < 0.33$), which have available flux measurements of the $H\alpha$ emission line. The black points represent the galaxies which have a quality flag $f=1$ assigned to their spectra, whereas the red points stand for the AGNs, as identified by the BPT diagnostic diagram, which do not have reliable sSFR estimates. The red solid line represents the main sequence of star forming galaxies for a redshift of $z \sim 0.2$ as derived by Peng et al. 2010. The plot on the right-hand side shows the sSFR-M relation for the high redshift field galaxies ($0.36 < z < 0.9$). The SFRs for high z galaxies were computed based on the luminosity of the [OII] line. Only $f=1$ field galaxies are shown in this plot. The solid and dotted lines represent the main sequence of SF galaxies at a redshift of $z \sim 0.5$ with its scatter. If galaxies lie ± 0.3 dex around the red solid line, then the systems belong to the star forming main sequence.

forming galaxies. Given the typical uncertainties of $\sim \pm 0.03$ dex in the estimation of sSFRs, most of the field galaxies populate the MS, with a smaller fraction of systems falling below the MS and thus being classified as passive galaxies. Only a minor number of field galaxies show enhanced sSFRs, falling above the MS in the sSFR-M plane.

5.4 Mass-Metallicity relation

Stellar masses and the gas-phase metallicities represent two of the most fundamental physical properties of galaxies, as they both give an insight into the processes governing galaxy evolution. The stellar mass is a metric indicating the amount of gas locked up into long lived stars whereas the metallicity describes the reprocessing of gas by stars and reflects any interaction between the galaxy and its environment. Observations have shown that there is a strong correlation of ~ 0.1

dex between the gas phase metallicity of a galaxy and its stellar mass, with high mass galaxies showing more enhanced gas-phase metallicities than low mass ones. It is crucial to understand the relation between these two quantities and how it evolves with time in order to grasp the processes that influence the efficiency and timing of star formation [9].

Spectroscopic observations of the local universe have allowed us to analyse both the stellar and gas-phase metallicities of galaxies as well as the variation of these properties across different galaxy types.

5.4.1 Derivation of oxygen abundances

The oxygen abundances for the RXJ2248 cluster members were computed by means of 3 empirically calibrated metallicity estimators based on the relative strengths of emission lines: the calibration by Kewley et. al 2013 which uses the O3N2 index together with the $[OIII]/H\beta$ and the $[NII]/H\alpha$ line ratio calibrations derived by Maier et al. 2016. For the comparison sample of field galaxies, the gas phase metallicities were calculated by means of the O3N2 calibration of Kewley et. al 2013, and the $[OIII]/H\beta$ line-ratio calibration by Maier et al. 2016.

The O3N2 index was first introduced by Alloin et al. 1979 as:

$$O3N2 = \log([OIII]\lambda 5007/H\beta)/([NII]\lambda 6583/H\alpha) \quad (5.35)$$

This index relies on ratios of emission lines which are close in wavelength, so that corrections for reddening, and accurate flux calibration of the spectra, are not necessary [59]. Just the $H\beta$ line flux has been corrected for absorption as proposed by Kobulnicky et al 1999. By means of current stellar evolutionary synthesis and photoionization models with chemical evolution measurements from cosmological hydrodynamic simulations, Kewley et. al 2013 came up with the following empirical metallicity calibration based on the O3N2 index:

$$12 + \log(O/H) = 8.97 - 0.32 \cdot O3N2 \quad (5.36)$$

This calibration corresponds to the Pettini and Pagel et al. 2004 O3N2 calibration for the Kewley and Dopita et al. 2002 metallicity scale, with a difference in the normalisation factor of +0.24. This metallicity calibration is one of the most popular methods used, both at low and higher redshift, as it is only weakly affected by differential extinction and it utilises the strongest emission lines, which are easily accessible for rest-frame optical spectroscopy. This calibration has been used for all the RXJ2248 star forming cluster members as well as for the field population with available measurements of the 4 emission lines of interest in order to derive oxygen abundances [60].

Maier et al. 2016. derived two new (O/H) calibrations for galaxies on the star-forming sequence, one as a function of the $[OIII]/H\beta$ line ratio and the other as a function of $[NII]/H\alpha$. These two metallicity calibrations are based on equations 3. and 4. of Kewley et al. 2013:

$$\log([OIII]/H\beta) = \frac{0.61}{\log([NII]/H\alpha) + 0.08} + 1.1 \quad (5.37)$$

$$12 + \log(O/H) = 8.97 - 0.32 \cdot O3N2 \quad (5.38)$$

The calibration as a function of the line ratio $[OIII]/H\beta$ is very practical as a metallicity indicator for high-redshifted galaxies which do not have measurements of the $[NII]\lambda 6583$ and $H\alpha$ emission lines. The metallicity calibration based on these 2 emission lines is given by the following equation:

$$12 + \log(O/H) = 8.97 - 0.32 \cdot (\log([OIII]/H\beta) - 0.61/(\log([OIII]/H\beta) - 1.1) + 0.08) \quad (5.39)$$

Corrections for extinction and accurate flux calibration of the spectra are not necessarily needed, as the lines $[OIII]$ and $H\beta$ are close in wavelength [15]. This metallicity estimator was used to compute the (O/H) for the cluster members and for the high-redshift sample of comparison field galaxies which have no measurements of the $[NII]$ and $H\alpha$ lines.

The empirical (O/H) calibration as a function of the $[NII]/H\alpha$ line ratio, derived by Maier et al. 2016 can be expressed as follows [15]:

$$12 + \log(O/H) = 8.97 - 0.32 \cdot (1.1 + 0.61/(\log([NII]/H\alpha) + 0.08) - \log([NII]/H\alpha)) \quad (5.40)$$

Equation 5.40 is similar to the (O/H) calibration of Salim et al. 2015, which uses the re-calibrated N_2 index, that matches the Pettini and Pagel et al. 2004 O3N2 metallicity calibration. Thus, the calibration from this work corresponds to the equation 4. of Salim et al. 2015:

$$12 + \log(O/H)_{N2} = a + bN2 + c/(N2 - d) \quad (5.41)$$

with the coefficients $a = 8.618$, $b = 0.32$, $c = -0.1952$, and $d = -0.08$. The calibration derived by Salim et al. 2015 has slightly different coefficients: $a = 8.50$, $b = 0.37$, $c = -0.15$, $d = -0.10$. The authors of this paper have demonstrated that the $[NII]/H\alpha$ calibration delivers accurate metallicity values up to $(12 + \log(O/H)N2) = 8.86$. Above a threshold $(12 + \log(O/H)N2) > 8.9$, the $N2$ -method saturates, and the computed (O/H) values should not be taken in account [61]. However, as the calibration by Maier et al. 2016 uses slightly different parameters, this upper threshold will not be applied, but one should keep in mind that this calibration saturates for high oxygen abundance values. Again, corrections for extinction as well as accurate flux calibrations are not needed, as the used emission lines are close in wavelength. This metallicity calibration was used for the whole sample of RXJ2248 cluster members to derive oxygen abundances.

5.4.2 MZR for RXJ2248 cluster members

The MZ relation determined from emission-line diagnostics was introduced as first by Tremonti et al. 2004, who found a tight correlation of 0.1 dex between stellar mass and the gas-phase oxygen abundance, which extends over 3 orders of magnitude in stellar mass and a factor of 10 in oxygen abundance.

Fig. 5.14 shows the mass-metallicity relation for the RXJ2248 cluster members: the y-axis plots the oxygen abundance as derived through the O3N2 metallicity calibration of Kewley et al. 2013 and the x-axis plots the stellar masses of the cluster members in solar units. The panel from the left-hand side shows the MZR for all cluster members with available measurements of the 4 emission lines $[OIII]$, $H\beta$, $[NII]$ and $H\alpha$ needed to compute the O3N2 index. The different colour codes stand for the quality flags assigned to the spectra: the black points represent the cluster galaxies, which have a quality flag $f=1$ describing their spectra, the blue points represent the galaxies which have a quality flag $f=2$ assigned to their spectra whereas the red points stand for the galaxies described by a $f=3$. The cyan diamonds and solid curve represent the MZR as derived by Tremonti et al. 2004 for a sample of local galaxies, observed as part of the Sloan Digital Sky Survey. The gas phase metallicities of these local galaxies were also derived using the O3N2 metallicity calibration. The dotted cyan curves represent the 1σ scatter of this relation. The MZR for the SDSS sample was extrapolated down to lower masses of $\log(M/M_{\odot}) = 8$ by assuming that the slope remains constant for $\log(M/M_{\odot}) < 9.2$. The black cross in the upper left corner represents the mean error of the metallicity derivation. The panel on the right-hand side shows the MZR for the RXJ248 cluster members with accurate flux measurements, which were selected for the metallicity study as described in section 4.3.1. In this panel, we also show the AGNs in red, as classified by the BPT diagnostic diagram. The open green diamonds represent the median values of the gas phase metallicity of the cluster galaxies, which were divided into 2 mass bins: $8.3 < \log(M/M_{\odot}) < 9.5$ (low M bin) and $9.5 < \log(M/M_{\odot}) < 11$.

In appendix C.1, we show the MZR of cluster galaxies as derived using the 2 metallicity calibrations computed by Maier et al. 2016: the $[OIII]/H\beta$ and $[NII]/H\alpha$ metallicity estimators, see figures C.1 and C.2.

Based on these diagrams, one can conclude the following: galaxies from the low mass bin show more enhanced metallicities than SDSS galaxies, with the median (O/H) value of cluster members being by ~ 0.1 dex higher than the median (O/H) value of local galaxies, while at the high mass end, most galaxies show lower metallicities than the sample of local galaxies, but only by a very small factor, as most of them fall within the $\sim 1\sigma$ dispersion of the local SDSS MZR.

Fig. 5.15 displays the difference between the oxygen abundances calculated using the O3N2

calibration and the metallicities calculated using the $[OIII]/H\beta$ line ratio method as a function of the O3N2 metallicities. The plot from the left-hand side shows the difference between the (O/H)s obtained by means of these two different metallicity calibrations for the whole sample of RXJ2248 cluster members with available measurements of the $[OIII]$, $H\beta$, $[NII]$ and $H\alpha$ emission lines. The colour codes are the same as in the previous fig. The plot on the right-hand side also shows the difference in the computed (O/H)s but just for the sample of galaxies which were selected for the metallicity study.

As can be seen from the 2 plots, the metallicity calibration based on the $[OIII]/H\beta$ emission line ratio offers lower values for the oxygen abundance than the O3N2 method. This is due to the fact that $[OIII]$ and $H\beta$ lines can be weak in the integrated optical spectra of galaxies, and metallicity calibrations based purely on these two lines tend to yield lower metallicity values than when using a calibration based on more emission lines.

However, by taking in account the typical uncertainties of $\sim \pm 0.06$ dex in the oxygen abundance derivation, there is a pretty good agreement between the O3N2 and the $[OIII]/H\beta$ calibration, of course, with a few exceptions. As expected, the galaxies classified as AGNs show the highest discrepancy between the (O/H)s computed through the 2 methods. The other galaxies which have $(O/H)_{O3N2} - (O/H)_{[OIII]/H\beta} > 0.15$ mostly fall in the composite zone of the BPT diagram, meaning that their ionisation comes from both an AGN and the stellar component. Thus, the (O/H)s derived for these galaxies are not that accurate and should not be taken into account.

Fig. 5.16 shows the difference between the oxygen abundances calculated through the O3N2 calibration and the metallicities derived by means of the $[NII]/H\alpha$ line ratio method as a function of the O3N2 calibration. The panel from the left-hand side shows the difference between the (O/H)s obtained through these two different calibrations for the whole sample of RXJ2248 cluster members with available measurements of the $[OIII]$, $H\beta$, $[NII]$ and $H\alpha$ emission lines. The colour codes are the same as in the previous plots. The panel on the right-hand side also shows the difference in the derived metallicities, but only for the sample of galaxies which have accurate measurements of all emission lines of interest. The black points represent the galaxies whose spectra are described quality flag $f=1$ and the red points represent the cluster AGNs.

As can be seen from the 2 plots, the $[NII]/H\alpha$ metallicity calibration yields higher values for the more enhanced oxygen abundances than the O3N2 method. An explanation for this is given by the fact that $[NII]$ and $H\alpha$ lines are the strongest spectral features in the optical spectra of galaxies, and metallicity calibrations based purely on these two lines will offer slightly higher (O/H) values than when using a calibration based on more emission lines. Nonetheless, given the typical uncertainties in the derivation of oxygen abundances, there is a pretty good agreement

between the two metallicity calibration, but again, with a few exceptions. As stated earlier, the calibration based on the $[NII]/H\alpha$ line ratio is known to saturate for high (O/H) values and does not offer accurate metallicities above a specific threshold. Again, the galaxies classified as AGNs show the highest discrepancy between the metallicities derived through these 2 methods. 2 AGNs fall far below the axis limits, having a value of $(O/H)_{O3N2} - (O/H)_{[NII]/H\alpha} \sim -0.8$. The other galaxies which have $(O/H)_{O3N2} - (O/H)_{[NII]/H\alpha} < -0.15$ fall in the "uncertainty region" of the BPT diagram, between the two theoretical curves which divide SF galaxies from AGNs, meaning that their ISM is ionised by both an AGN and the stellar component. Hence, the (O/H) s derived through the $[NII]/H\alpha$ method for the composite galaxies should not be taken into consideration, because the abundances are not accurate, as we know that this metallicity calibration is suited just for normal, star forming galaxies.

Fig. 5.17 shows the offset of the MZR of RXJ2248 cluster galaxies to the local SDSS MZR, as a function of the stellar masses of these galaxies. The plot on the left-hand side shows the offset to the local SDSS MZR for all cluster members which have measurements of the emission lines of interest, while the plot on the right-hand side shows the offset to the SDSS MZR as well, but only for cluster members which have a quality flag $f=1$ assigned to their spectra. The colour codes are the same as in the previous plots. The median values of the offset are also shown as green open diamonds.

In appendix C.1, we also show the offset of the MZR of cluster galaxies to that of the local SDSS galaxies, as computed through the $[OIII]/H\beta$ and $[NII]/H\alpha$ metallicity calibrations, see fig. C.3 and C.4.

It is clear from these diagrams that the cluster population at a redshift of $z \sim 0.35$ has chemical abundances that differ from the abundances of the local galaxies. However, given the typical uncertainties of ~ 0.06 dex in the estimation of gas phase metallicities, one can state that the majority of the RXJ2248 cluster galaxies are in accordance to the local SDSS MZR, to within 1σ .

The highest offsets to the local MZR can be seen for the lowest mass galaxies ($\log(M/M_\odot) < 9.5$), which generally show higher metallicities than the sample of low z galaxies from the local universe. The median value of the (O/H) s of cluster galaxies at the low mass end is by ~ 0.1 dex higher than that of local galaxies. At the highest masses, however, this trend is reversed with most galaxies showing lower oxygen abundance values than the local SDSS sample, by ~ 0.03 dex.

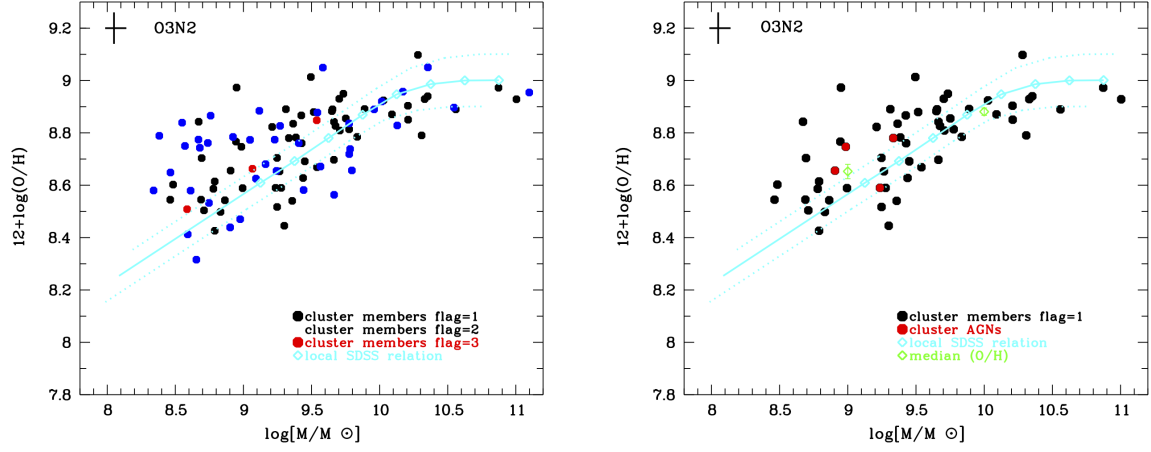


Figure 5.14: MZR for RXJ2248 cluster members using the O3N2 metallicity calibration of Kewley et al. 2013. The panel from the left-hand side shows the MZR for all cluster members with available measurements of the $[OIII]$, $H\beta$, $[NII]$ and $H\alpha$ lines. The colour codes black, red and blue stand for the different quality flags assigned to the spectra. The panel from the right-hand side shows the derived MZR for the cluster members with accurate line measurements, which were selected for the metallicity study. The red points represent the AGNs, as identified by the BPT and WHAN diagnostic diagrams. In both panels, the cyan diamonds and curves represent the local SDSS relation with its 1σ scatter. The black cross in the upper left corner represents the mean error of the (O/H) derivation.

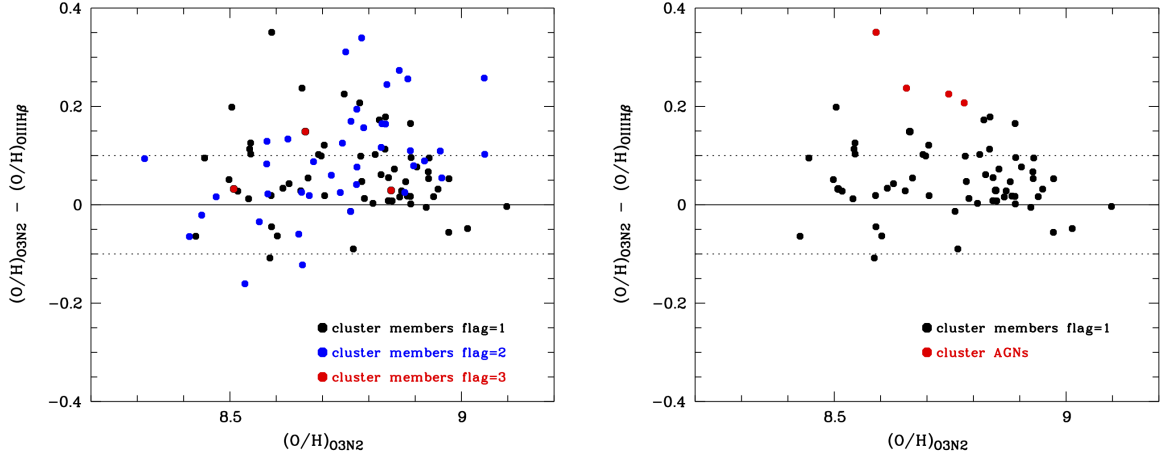


Figure 5.15: The difference between the (O/H) s calculated by means of the $O3N2$ calibration and the (O/H) s calculated using the $[OIII]/H\beta$ method. The plot from the left-hand side shows the difference in (O/H) s as calculated through the 2 methods for all cluster members with available measurements of the emission lines $[OIII]$, $H\beta$, $[NII]$ and $H\alpha$. The colour codes denote the different quality flags assigned to the spectra. The plot on the right-hand side shows the difference between the (O/H) s calculated through the 2 different metallicity calibrations, but only for the galaxies with accurate measurements of the emission lines. The black points stand for galaxies with $f=1$ and the red points represent the AGNs. By taking into account the typical uncertainties of $\sim 0.1 - 0.2$ dex in the oxygen abundance derivation, there is a pretty good agreement between the $O3N2$ method and the $[OIII]/H\beta$ metallicity calibration, but with some outliers.

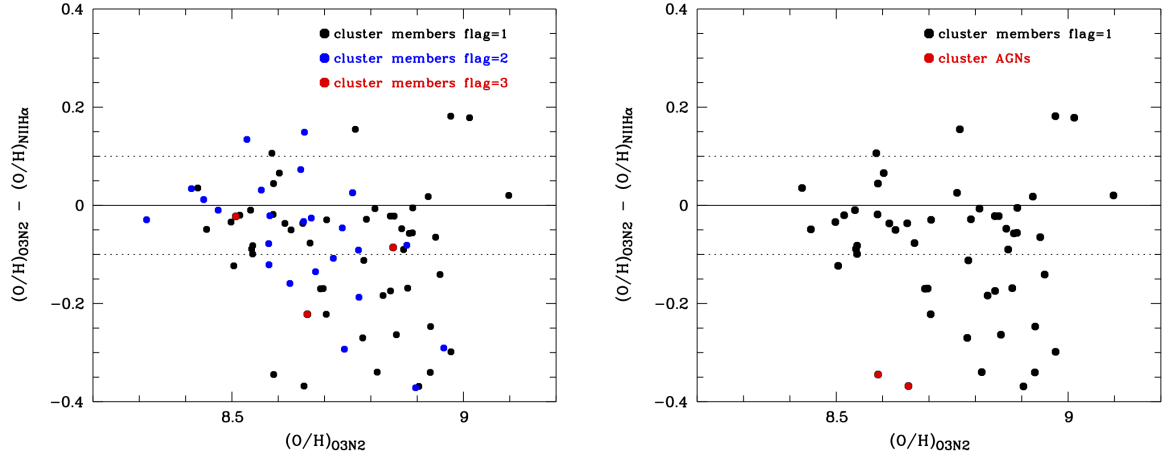


Figure 5.16: The difference between the (O/H) s derived through the O3N2 calibration, and the (O/H) s calculated using the $[NII]/H\alpha$ method. The panel from the left-hand side shows the difference in (O/H) s, as calculated through the 2 methods, for all cluster members with available measurements of the emission lines $[OIII]$, $H\beta$, $[NII]$ and $H\alpha$. The colour codes stand for the different quality flags describing the spectra. The plot on the right-hand side shows the difference between the (O/H) s calculated through the 2 different methods, but only for the galaxies which were selected for the metallicity study. The black points show the galaxies described by $f=1$ and the red points show the AGNs. By taking into account the typical uncertainties of $\sim 0.1 - 0.2$ dex in the derivation of oxygen abundances, there is a pretty good agreement between the O3N2 method and the other 2 metallicity calibrations, but with some exceptions.

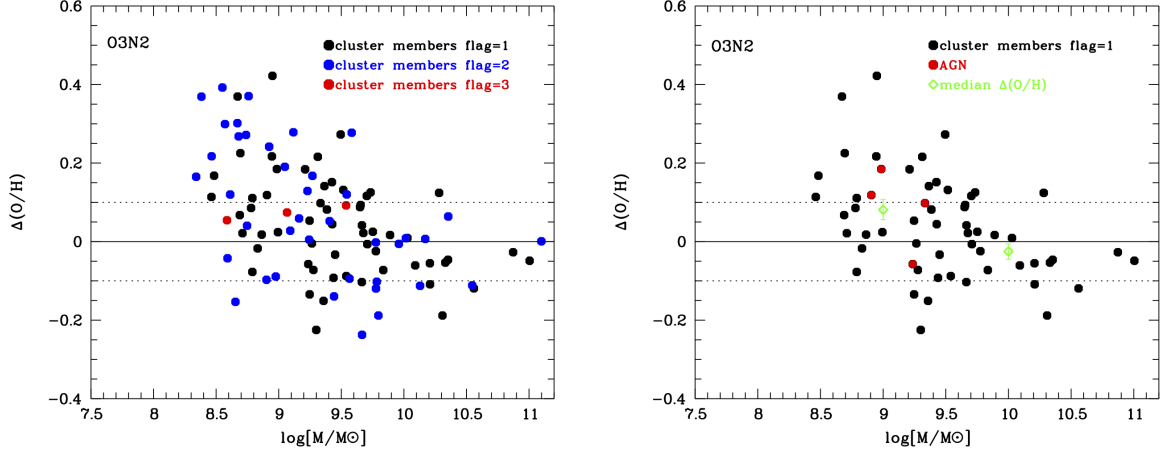


Figure 5.17: The median offset to the local SDSS MZR for the RXJ2248 cluster members, whose (O/H)s were calculated through the O3N2 calibration. The plot on the left-hand side shows the offset to the local MZR for all cluster members with available flux measurements, while the panel from the right-hand side shows the same, but only for the members which have a quality flag $f=1$ assigned to their spectra. The median values of this offset are shown as open green diamonds.

5.4.3 MZR for field sample

Fig. 5.18 shows the derived oxygen abundances using the O3N2 metallicity calibration of Kewley et al. 2013 as a function of the stellar masses, for both field galaxies from the low redshift bin $0.01 < z < 0.33$ (left) and high redshift bin $0.36 < z < 0.9$ (right). The black points in both diagrams represent the field galaxies, which have a quality flags $f=1$ assigned to their spectra. The cyan diamonds and solid curve represent the MZR of local SDSS galaxies, while the dotted lines stand for the 1σ scatter of this local MZR. The cross from the upper left corner in both diagrams shows the median error in the (O/H) derivation.

Fig. 5.19 shows the median offset of the measured gas phase metallicities of field galaxies to the local SDSS MZR as a function of the stellar masses. The black dots in both diagrams stand for the field galaxies, whose spectra are characterised by a quality flag $f=1$.

In general, field galaxies from both redshift bins, with $\log(M/M_\odot) < 9$, show more enhanced gas phase metallicities than local galaxies, whereas this trend is reversed for the high mass end. Nevertheless, given the typical uncertainties in the (O/H) derivation, most field galaxies are in accordance to the observed MZR of local galaxies, with high mass galaxies having higher gas metallicities than low mass ones. When comparing the (O/H)s of field galaxies from the low and

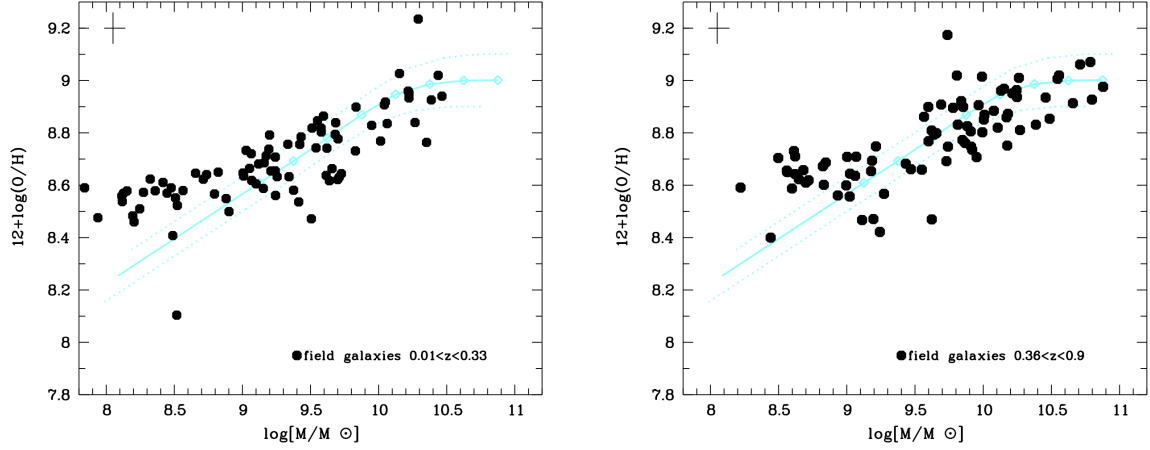


Figure 5.18: MZR for field galaxies using the O3N2 metallicity calibration of Kewley et al. 2013. The panel from the left-hand side shows the MZR for the field galaxies from the low redshift bin, while the graph from the right-hand side displays the MZR for the high-redshift field galaxies. The black, filled dots stand for the $f=1$ field galaxies, which have available flux measurements of the $[OIII]$, $H\beta$, $[NII]$ and $H\alpha$ lines. The cyan diamonds and curves represent the local SDSS relation with its 1σ scatter. The crosses from the upper left corners display the mean errors of the (O/H) derivation.

high redshift bin, no substantial differences can be seen. In appendix C.2, we show the MZR of field galaxies, as computed through the $[OIII]/H\beta$ metallicity calibration, see figure C.5. The offset of field galaxies to the local SDSS MZR, as computed through the $[OIII]/H\beta$ method is also shown here, see fig. C.6.

5.5 Comparison cluster to field galaxies

In order to accurately compare both the sSFR and (O/H) s of cluster and field galaxies, the samples have been divided into 2 mass bins: $8.3 < \log(M/M_\odot) < 9.5$ (low M bin) and $9.5 < \log(M/M_\odot) < 11$ (high M bin). These 2 mass bins were chosen as such, in order to have a similar number of galaxies in each bin. For each mass bin, the median value for both the gas metallicity and the sSFR were calculated with help of a python code, using the *statistics* package. The median of a distribution "a" with n entries is given by:

$$median(a) = \frac{a_{[n \div 2]} + a_{[n \div 2 + 1]}}{2} \quad (5.42)$$

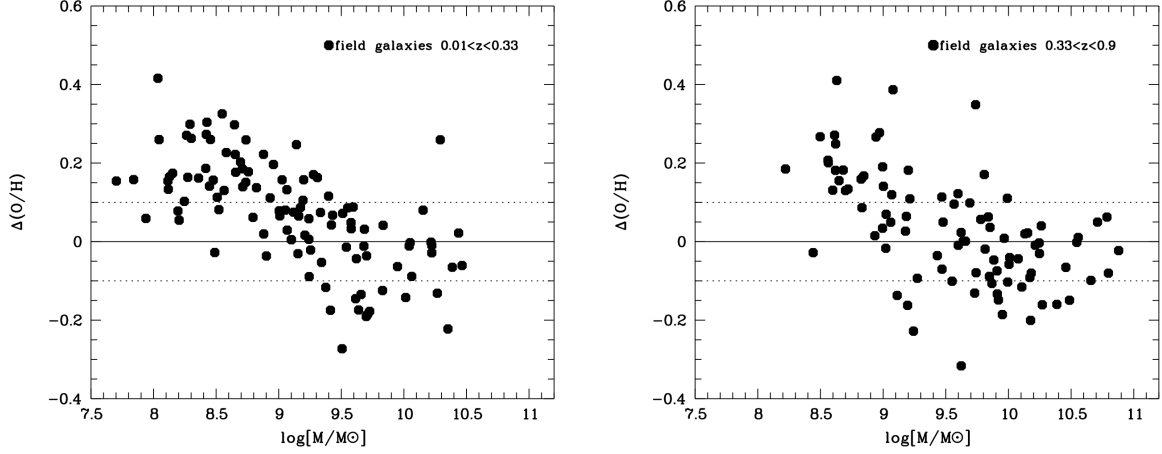


Figure 5.19: The median offset of the (O/H)s of field galaxies from the low (left) and high (right) redshift bin, whose gas phase metallicities were calculated through the O3N2 calibration, to the MZR of local SDSS galaxies.

where $a_{[n]}$ represents the last element of the distribution.

The standard error of the median is then given by:

$$\sigma_{median}(a) = \frac{a_{[84\%]} - a_{[16\%]}}{\sqrt{n}} \quad (5.43)$$

with $a_{[84\%]}$ and $a_{[16\%]}$ representing the number which occupies the 84% and 16% position in the data set a . When comparing the median (O/H) values of sSFRs and (O/H)s of cluster and field galaxies, it is also important to consider the statistical significance of the differences between these 2 populations. This is done by means of the following equation:

$$significance = \frac{median(a)_{field} - median(a)_{cluster}}{\sqrt{(\sigma_{median}(a)_{field})^2 + (\sigma_{median}(a)_{cluster})^2}} \quad (5.44)$$

It is also worth mentioning that only field galaxies with $0.3 < z < 0.4$ were chosen as a comparison sample to the cluster galaxies, in order to avoid any biases with galaxy evolution.

Fig. 5.20 shows the sSFR-M relation for the RXJ2248 cluster galaxies (black symbols) and for the field galaxies (blue symbols.) The plot on the left-hand side shows the sSFR derived through the luminosity of the $H\alpha$ emission line, as a function of the stellar mass, for all cluster and field galaxies, whose spectra are described by a quality flag $f=1$. The plot on the right-hand side shows the median values for the sSFR-M and the standard error of the median for both cluster and field galaxies. The red solid line and the red dashed lines represent the MS of SF galaxies, as derived by Peng et al. 2010 for a redshift of $z \sim 0.4$. The median sSFR values were calculated using eq. 5.42, for the 2 aforementioned mass bins. The number of galaxies in each mass bin is shown on the graph.

Both cluster and field galaxies can be classified as MS SF galaxies, but of course, there are some outliers. The median sSFR of field galaxies seems to be higher than the median sSFR of cluster galaxies at the low mass end, but only by ~ 0.1 dex with a $\sim 0.5\sigma$ significance. For the low mass bin of $\log(M/M_\odot) < 9.5$, the median sSFR for the cluster galaxies is -0.41, and for field -0.29. For the high mass end, this trend is reversed, with cluster galaxies showing more enhanced sSFRs than the field population, by a factor of ~ 0.2 dex, with a $\sim 0.43\sigma$ significance. In the high mass bin of $\log(M/M_\odot) > 9.5$, we observe a median sSFR for cluster members of -0.381 and for the field galaxies of -0.624. However, we should also mention that the errors of the median are fairly high in this high mass regime.

Given the uncertainties of $\sim 0.03dex$ in the estimation of the SFRs, and due to the fact that only SF galaxies are considered within this work, no substantial differences between the sSFRs of field and cluster galaxies can be observed. The median values of the sSFRs of both populations seem to be in accordance with the predicted scatter of 0.3 dex of the MS of SF galaxies. Therefore, the mass-sSFR relation of SF galaxies from this sample seems to be rather independent of whether the galaxies populate the field or cluster. These results are consistent with the findings of Maier et al. 2016 and Maier et al. 2019 who observed a similar distribution for members of CLASH and LoCuSS clusters and for field galaxies in the mass-sSFR plane [15, 63].

Fig. 5.21 shows the MZR for RXJ2248 cluster galaxies (black symbols) and the comparison sample of field galaxies with $0.3 < z < 0.4$ (blue symbols). The plot on the left-hand side shows the MZR for field and cluster galaxies, which have accurate measurements of the $[OIII]$, $[NII]$, $H\alpha$, $H\beta$ emission lines, having a quality flag $f=1$ assigned to their spectra. The oxygen abundances were computed using the O3N2 calibration of Kewley et al. 2013. The graph on the right-hand side shows the median values of the MZR of cluster and field galaxies. The median values were calculated using eq. 5.42 and by dividing the sample into 2 mass bins, exactly as for the sSFR-M comparison between field and cluster. The cyan curves in both panels represent the MZR for local SDSS galaxies, as derived by Tremonti et al. 2004.

Cluster members at low stellar masses, with $\log(M/N_\odot) < 9.5$ seem to have higher (O/H)s than field galaxies, while at the high mass end, both field and cluster galaxies have similar gas phase metallicities. The median value of the (O/H)s of cluster galaxies from the low mass bin is by 0.05 dex higher than the median (O/H) value of field galaxies, yielding a $\sim 1.1\sigma$ significance. At the high mass end, the median values of the (O/H)s of cluster and field galaxies differ only by 0.03dex, with a $\sim 0.1\sigma$ significance. By taking the uncertainties of ~ 0.06 dex of the (O/H) computation into account, at a first glance, no substantial difference can be seen between cluster and field galaxies, at least at the high mass end. Both populations show slightly more enhanced

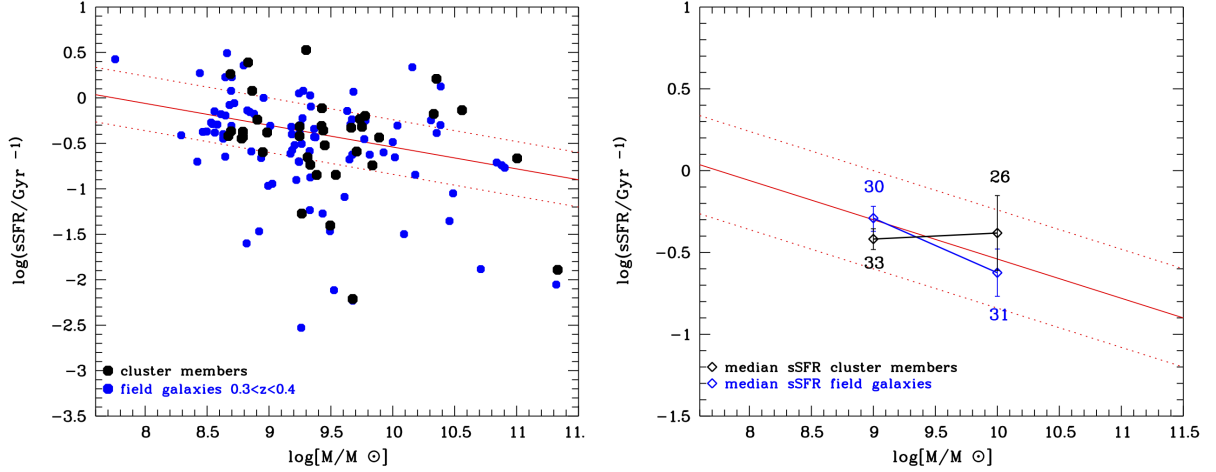


Figure 5.20: The plot on the left-hand side shows the sSFR-M relation for the RXJ2248 cluster galaxies (black symbols) and the comparison sample of field galaxies (blue symbols). The graph on the right-hand side displays the median values of the sSFR-M for cluster galaxies at $0.33 < z < 0.36$ and field galaxies at $0.3 < z < 0.4$. The red solid and red dashed lines represents the MS of SF galaxies at $z \sim 0.4$ together with its 0.3 dex dispersion.

metallicities than the local SDSS MZR at the low stellar masses, but they follow this relation at the high-mass end within 1σ . These observational findings are further explored in the sections that follow.

For cluster and field galaxies from the low mass end, there seems to be an anti-correlation between sSFR and metallicities, this being an expected result due to the FMR: at a given stellar mass, galaxies with high (O/H)s will show lower sSFRs.

5.6 Cluster membership

Clusters of galaxies are the most massive, virialized systems in the universe, which makes them perfect cosmological laboratories. According to the Λ CDM cosmological model, such massive structures are formed hierarchically through aggregation of smaller systems. Clusters are surrounded by infall regions where galaxies from the field can be accreted. These recently accreted galaxies are gravitationally bound to the cluster but are not yet in dynamical equilibrium with the cluster potential, and therefore, they should not be used to derive the clusters' mass.

The dynamical masses of clusters are generally derived from the virial mass estimator. This method has however a drawback, as it makes assumptions about the dynamical state of the sys-

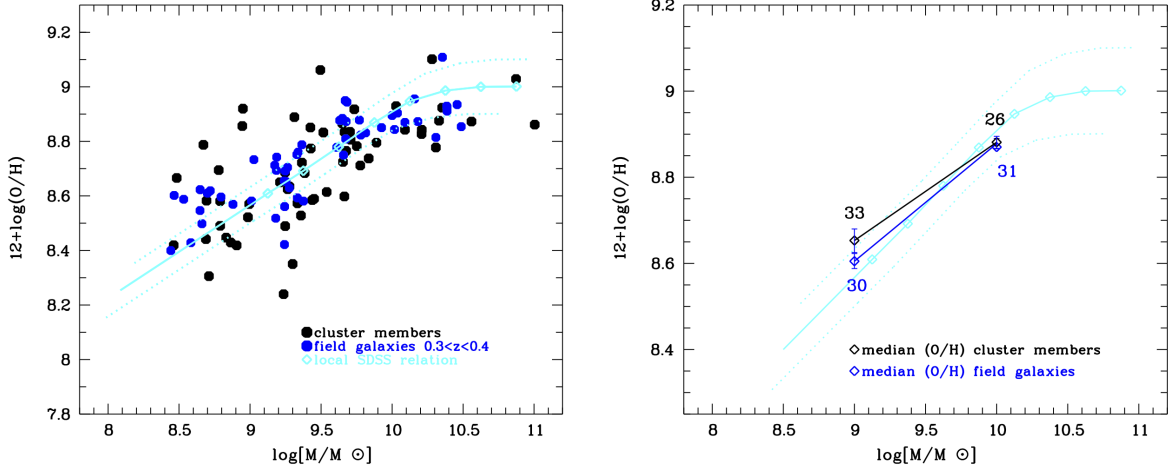


Figure 5.21: The plot on the left displays the MZR for RXJ2248 cluster galaxies (black symbols) and the comparison sample of field galaxies (blue symbols). The graph on the right-hand side shows the median values of the MZR for cluster galaxies at $0.33 < z < 0.36$ and field galaxies at $0.3 < z < 0.4$. The cyan curve represents the MZR for local SDSS galaxies.

tem. The reliability of this approach is dependent on the cluster members being in dynamical equilibrium with the gravitational potential, so the virial theorem should apply:

$$2E_{kin} + E_{pot} = 0 \implies M\langle v^2 \rangle + \frac{GM^2}{R_g} = 0 \quad (5.45)$$

with M being the total mass, G the gravitational constant and R_g the gravitational radius. If the system is in virial equilibrium, then the velocity dispersion of the cluster members (in the cluster rest-frame) is:

$$\sigma^2 = \langle v^2 \rangle \quad (5.46)$$

and thus

$$\sigma^2 R \sim GM(< R) \quad (5.47)$$

The criterion for a galaxy to be gravitationally bound is:

$$E_{kin} < |E_{pot}| \quad (5.48)$$

which means that:

$$\sigma^2 = \langle v^2 \rangle < 2 \cdot \frac{GM}{R} \quad (5.49)$$

σ can be calculated as:

$$\sigma = \frac{c}{1 + \bar{z}} \cdot \sqrt{\frac{1}{1 - N} \sum_{i=1}^N (z_i - \bar{z})^2} \quad (5.50)$$

where z_i stands for the redshifts of the individual cluster members and $\bar{z}$ represents the mean redshift of the cluster [64].

Several methods exist to investigate the cluster membership for a spectroscopic data-set, one of the simplest and most straight forward being the 3σ -clipping technique of Yahil & Vidal 1977. This approach assumes that clusters are relaxed isothermal spheres and therefore, the velocity distribution of the cluster galaxies will follow an underlying Gaussian distribution. This method uses the redshift distribution of the cluster galaxies and applies an upper and a lower bound. Then, the mean and standard deviation of the galaxies is calculated (eq. 5.50), followed by an iteration of this whole procedure. Generally, galaxies within 3σ will be classified as cluster members. Any galaxy, which is found to be beyond 3σ is considered to be a galaxy from the field. This statistical clipping approach to determine the cluster membership uses only one parameter, namely the inferred recession velocities of the cluster galaxies [65].

Another method to investigate the cluster membership was devised by Carlberg et al. 1997, which uses both the redshift and the spatial information to establish the "limits" of the cluster. This mass model was derived from a theoretical model which presumes that clusters are singular isothermal spheres (SIS), which can be described by the following density distribution:

$$\rho(R) = \frac{\sigma^2}{2\pi GR^2} \quad (5.51)$$

This SIS profile is unphysical because of the singularity at zero radius and also because of the fact that the total mass calculated by integrating the function out to an infinitely large radius does not converge. Due to its' simplicity, however, it is often used in the literature.

The mass model of Carlberg et al. 1997 works as follows: first, the difference in velocity Δv between the mean velocity of the cluster $c\bar{z}$ and the velocity of each individual galaxy is computed. Afterwards, the values of Δv are normalised to the clusters' velocity dispersion σ_z (eq. 5.50) and plotted against the projected cluster centric radius of the individual members in units of r_{200} . The parameter r_{200} represents the radius where density is 200 times the mean density of the universe and is derived as follows:

$$r_{200} = \frac{\sqrt{3}}{10} \cdot \frac{\sigma_z}{H(z)} \quad (5.52)$$

where σ_z is the velocity dispersion of the cluster and $H(z)$ for the redshift dependent Hubble parameter, which can be expressed through the following equation:

$$H(z)^2 = H_o^2(1+z)^2(1+\Omega_0 z) \implies H(0.35) = 81.791 km/(Mpc \cdot s) \quad (5.53)$$

M_{200} is then computed based on the following equation:

$$M_{200} = \frac{2r_{200}\sigma_z^2}{G} \quad (5.54)$$

The velocity dispersion profile used to mark the caustics within this model is calculated as follows:

$$\sigma^2 = B \cdot \frac{c_1 r / (1 + c_1 r) + c_2}{1 + r/b} \quad (5.55)$$

where $B = 1/4$ and $b = 0.66$ are two parameters adjusted to fit the observed projected velocity dispersion at R. The c_1 and c_2 parameters are fixed to be 0 and 1, respectively. This model is used to mark the 3σ and 6σ contours in the $\Delta v - r_{200}$ plane which separate between cluster members (within 3σ), near-field galaxies (between $3\sigma - 6\sigma$) and far-field galaxies (beyond 6σ). Spherical infall thus confines cluster members within such caustics defined by 5.55, which are contours with a characteristic trumpet shape [66].

This mass model by Carlberg et al. 1997 was implemented into a python code using the *astropy* and *matplotlib.pyplot* packages and by providing the code with a table containing the redshift, spatial coordinates, quality flag, stellar masses and oxygen abundances for field and cluster galaxies within a redshift range of $0.3 < z < 0.4$. The used cosmological parameters are in accordance to the Λ CDM model: $H_0 = 70 \text{ km Mpc}^{-1} \text{ s}^{-1}$, $\Omega_{m,0} = 0.27$, $\Omega_{\Lambda,0} = 0.73$. According to the implemented mass model, the RXJ2248 cluster can be described by the following parameters:

$$\begin{aligned} z_{cluster} &= 0.3458 \\ r_{200} &= 3.079 \text{ Mpc} \\ r_{500} &= 2.053 \text{ Mpc} \\ M_{200} &= 3.02 \cdot 10^{15} M_{\odot} \\ \langle v \rangle &= 1454.43 \text{ km/s} \end{aligned}$$

According to Gomez et al. 2012, the RXJ2248 cluster was considered to be one of the hottest and most luminous X-ray clusters known at that respective time. The high X-ray temperature, together with the high velocity dispersion, suggests that the system is very massive and/or a merging cluster. The authors of this paper also suggest that the velocity distribution of the RXJ2248 cluster members is better represented by the velocity dispersion produced during a merger event than by the velocity distribution of a relaxed cluster. Gomez et al. 2012 used the 3σ clipping method presented above to test the cluster membership and the $M_{200} - \sigma_{DM}$ scaling relation from Evrard et al. (2008) to compute $M_{200} = 2.46 \pm 0.31 \cdot 10^{15} M_{\odot}$ & $r_{200} = 3.15 \pm 0.25$ Mpc [67].

For example, in a more recent study by Melchior et al. 2015, the authors study the weak lensing masses and the galaxy distributions in massive clusters based on data from the Dark Energy Survey, and they derived a radius for RXJ2248 of $r_{200} \sim 2.2$ Mpc [68].

On the other hand, in a scientific publication by L. Pizzutia et al. 2017, the authors perform

a maximum likelihood kinematic analysis on the RXJ2248 cluster to determine the total mass profile in modified gravity models, assuming a spherical Navarro-Frenk-White profile, and obtained a value for $r_{200} = 2.7 \pm 0.12$ Mpc [69].

It is clear that the values for the cluster-specific parameters are dependent on the method chosen to compute them. Given the fact that the cluster in question is highly massive and presumed to be the remnant of a merger event, it is possible that the SIS mass model leads to an over-estimation of r_{200} and M_{200} . However, the computed values for these two parameters seem to be in pretty good agreement to the values found in the literature for the RXJ2248 cluster. The results to the cluster membership are presented into the section that follows.

5.7 Phase-space

Position vs. velocity diagrams offer great insight into the orbital histories of the cluster members. The location of galaxies in such projected phase space diagrams, i.e. cluster centric radius vs. line-of-sight velocity, provides information about the accretion history of the systems: virialized galaxies, that have been in the cluster for a few cluster crossings, will accumulate at low cluster centric radius and will have on average lower velocities, while the in-falling or recently accreted cluster galaxies will be found at higher velocities overall, and will be thus spatially separated from the accreted members. Different recent studies have used such phase-space diagrams in order to probe both the kinematics and the accretion epochs of the cluster members, as well as to constrain the density and mass profile of the cluster.

The membership of galaxies to the RXJ2248 cluster, as well as their accretion histories, were investigated by means of a phase-space diagram, see fig. 5.22, using the mass model by Carlberg et al. 1997, which was described in the previous section, in order to separate between cluster and field galaxies. All galaxies with spectroscopic redshifts between $0.3 < z < 0.4$ are considered. The red points located within the 3σ contours of the caustic profile (dark-grey area) are classified as being members of the RXJ2248 cluster. The blue diamonds, located between 3σ - 6σ (light-grey area) are classified as galaxies from the near field, while the black squares, which are located beyond 6σ (white area) are considered to be far-field galaxies. The sizes of the symbols correspond to 2 mass bins: the small dots stand for galaxies with $8.3 < \log(M/M_{\odot}) < 9.5$, and the big dots for galaxies with $9.5 < \log(M/M_{\odot}) < 11$. Only the red points are taken into account for the computation of r_{200} and M_{200} . To conclude, the virialized members of the cluster were identified as lying within the typical "trumpet shaped" caustic profile, having lower line of sight (l.o.s.) velocities than the near and far field galaxies, and being thus well spatially

separated from them.

The investigated cluster galaxies seem to be located, in projection, pretty close to the cluster core: all within $2 \cdot r_{2000}$. This is however not surprising, as the RXJ2248 cluster is known to be one of the most massive CLSH-VLT clusters. We know that the observations for the CLASH-VLT clusters were carried out by using 8-12 VIMOS pointings, with one quadrant locked onto the core of the cluster. For my thesis, I was provided with the set of observations from the crowded central region of the cluster. Therefore, most galaxies don't reach the limits of the caustic profile.

In order to further explore the accretion histories of cluster galaxies, a phase space diagram, which shows the 1σ and 2σ contours of the trumpet shaped caustic profile was computed for the RXJ2248 cluster members. This can be seen in fig. 5.23 and 5.24. Fig. 5.23 shows the location of cluster galaxies in projected phase space according to their mass: the large symbols represent the cluster galaxies with $9.5 < \log(M/M_{\odot}) < 11$, while the small ones stand for galaxies with $8.3 < \log(M/M_{\odot}) < 9.5$. Fig. 5.24 shows the distribution of the cluster members in projected phase space, according to the quality flag assigned to their spectra. The filled stars represent the sample of galaxies described by a quality flag $f=1$ and $f=2$, meaning that these systems show ELs in their spectra and are, thus, still actively forming stars. The open stars represent the passive galaxies, which show weak/no ELs in their spectra, being described by a quality flag $f=3$. The dashed black line in this plot shows the location of R_{500} , the radius at which the mean enclosed total mass over-density is 500 times higher than the density of the universe at the respective redshift, which was calculated as $R_{500} \sim \frac{2}{3} R_{200}$. In both figures, the red symbols which are located within the 1σ contour of the caustics (dark grey shaded area) are considered to be cluster galaxies, which were accreted longer ago and which possibly form a virialized population. These systems were most probably accreted into the cluster at earlier epochs, and the passive, quenched population probably passed through the apocentre of its first orbit. According to Haines et al. 2015, they identified this population of "accreted galaxies" as galaxies that either formed locally or that were accreted as the clusters core was being assembled. The blue symbols located between $2\sigma - 3\sigma$ (light grey shaded area) are classified as infalling galaxies, which have been recently accreted into the cluster, being still on their first passage, and which are not yet in dynamical equilibrium with the clusters' gravitational potential. Some of these systems have probably just recently passed within R_{200} for the first time, but have not yet reached the pericentre. Therefore, the population of infalling galaxies shows high line-of-sight velocities, as they are accelerated when they travel deep into the gravitational potential well of the cluster core [70]. All galaxies, regardless of the quality flag assigned to their spectra, are considered

here.

In appendix D, one can see the distribution of cluster galaxies in projected phase-space, colour coded according to their gas phase metallicities. No prominent metallicity effect can be observed when taking this approach. Both infalling and accreted cluster galaxies seem to have similar gas phase metallicities. Maier et al. 2016 and Maier et al. 2019 studied the chemical abundances of the members of CLASH and LoCuSS clusters, and found that infalling galaxies are less metal enriched than accreted galaxies, with both cluster populations showing more enhanced metallicities than their field counterparts. When comparing the metallicities of the RXJ2248 cluster galaxies to those of field galaxies, we also observe a weak metallicity effect at the low mass end, with cluster members showing more enhanced metallicities than their field population, see section 5.5 for more details. Maier et al., concluded that infalling/recently accreted galaxies enhance their metallicities while travelling towards the clusters' core. There are 2 possible scenarios to account for this: the systems either receive a metal enriched gas inflow into their halo, or the gas inflow rate into the galaxy is suppressed. The authors of these scientific papers, however, showed that the observed metallicity trends can be explained by mild ram pressure stripping.[15, 63]. These two scenarios are investigated in the sections that follow.

5.8 Tentative evidence for strangulation

5.8.1 (O/H) comparison between field galaxies and cluster members at different cluster centric radii

In order to further explore the environmental effect on the gas regulation within galaxies, we compare the median (O/H) values of field galaxies with $0.3 < z < 0.4$ to the median (O/H)s of cluster members with different accretion histories.

Figure 5.25 shows the MZR of field galaxies and accreted cluster members (left-hand side) and the MZR of field galaxies and infalling cluster galaxies (right-hand side), as classified according to their location in projected phase-space (within the 1σ contour of the caustic profile- accreted cluster members; between $1\sigma - 2\sigma$ contours: infalling cluster members). The black symbols represent the cluster galaxies, the blue ones the field population with $0.3 < z < 0.4$ and the cyan diamonds and curves the local SDSS MZR. Both galaxies described by a quality flag $f=1$ and $f=2$ are considered. The (O/H)s depicted here were computed using the O3N2 calibration of Kewley et. al 2013. For a meaningful investigation we divide the galaxies in our sample into two mass-bins: $8.3 < \log(M/M_{\odot}) < 9.5$ (low M bin) and $9.5 < \log(M/M_{\odot}) < 11$ (high M bin),

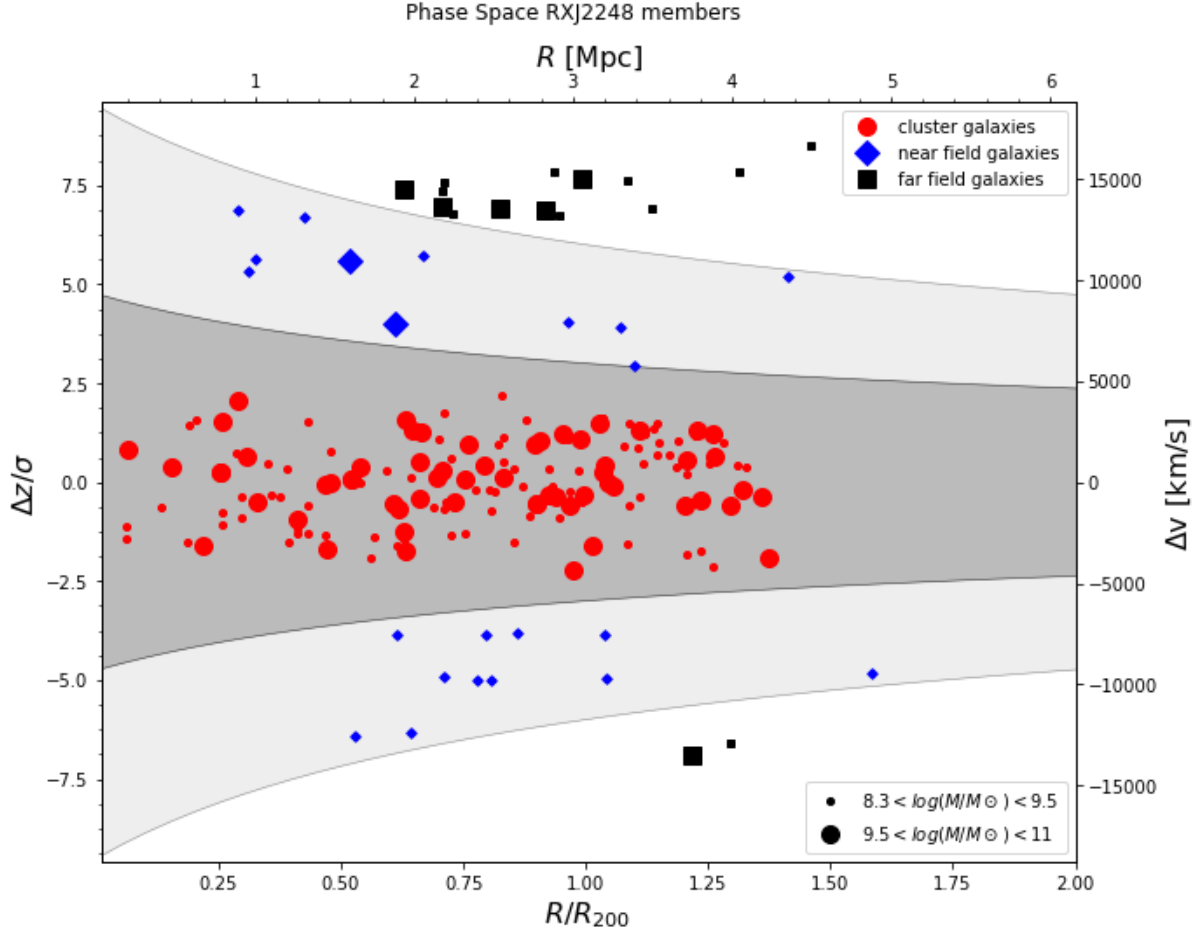


Figure 5.22: Cluster centric radius vs. line-of-sight velocity for field and cluster galaxies with $0.3 < z < 0.4$. The phase space diagram includes all galaxies from the sample, regardless of the quality flag assigned to their spectra. The red points which fall within the 3σ contours of the trumpet shaped caustic profile (dark-grey area) are classified as RXJ2248 cluster galaxies. The blue diamonds, located between 3σ - 6σ (light-grey area) contours are considered to be galaxies from the near field, whereas the black squares, which are located beyond 6σ are classified as far-field galaxies. The small symbols represent the low mass galaxies with $8.3 < \log(M/M_\odot) < 9.5$, while the large symbols stand for the high mass systems with $9.5 < \log(M/M_\odot) < 11$. Only the red points are considered for the computation of r_{200} and M_{200} .

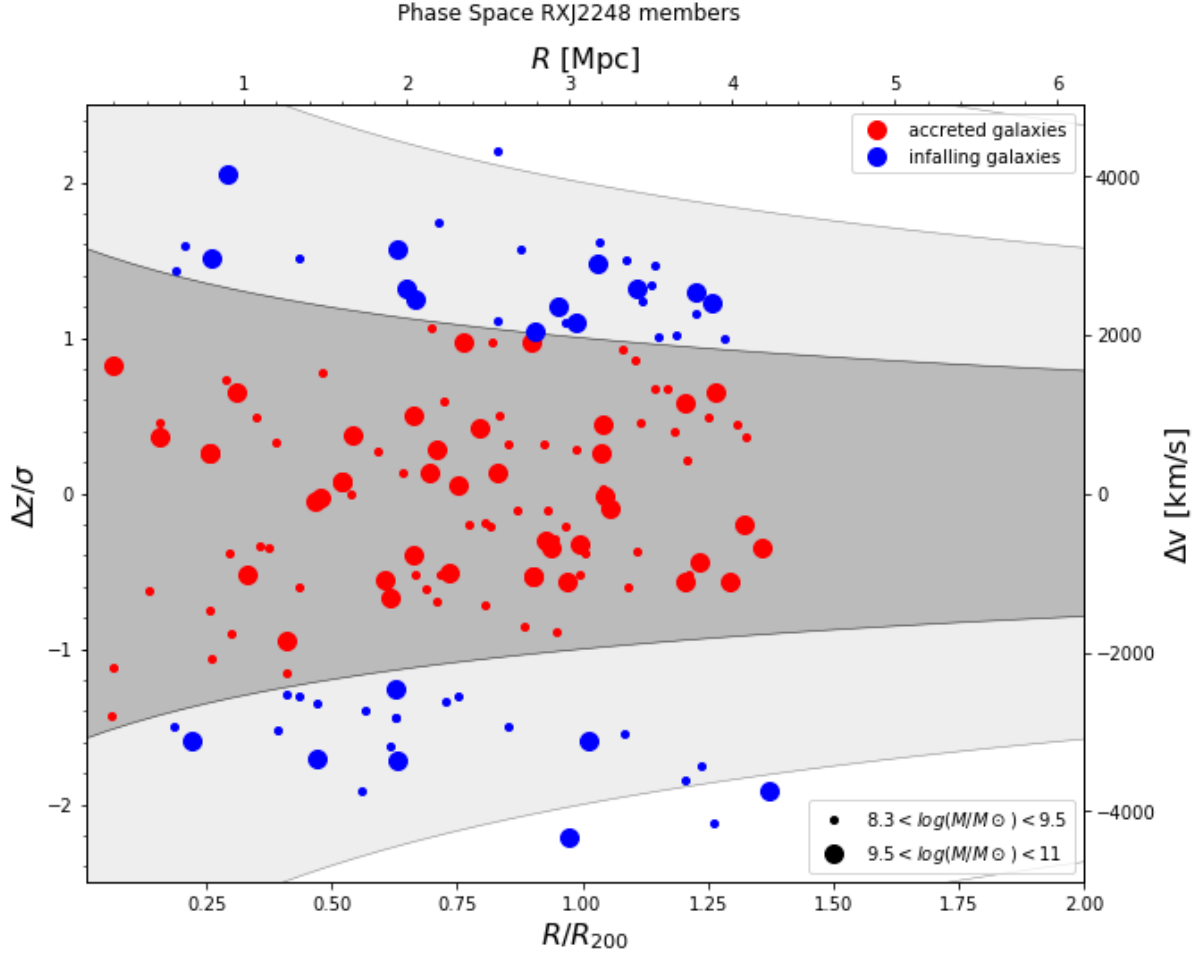


Figure 5.23: Cluster centric radius vs. line-of-sight velocity for the RXJ2248 cluster members. The red dots located within 1σ (dark-grey shaded area) are considered to be accreted and possibly virialised cluster members, which are in dynamical equilibrium with the clusters' potential. The blue symbols located between $2\sigma - 3\sigma$ (light grey shaded area) are classified as infalling galaxies, which have been just recently accreted into the cluster. The small symbols stand for the low mass galaxies with $8.3 < \log(M/M_\odot) < 9.5$, and the large symbols for the high mass systems with $9.5 < \log(M/M_\odot) < 11$.

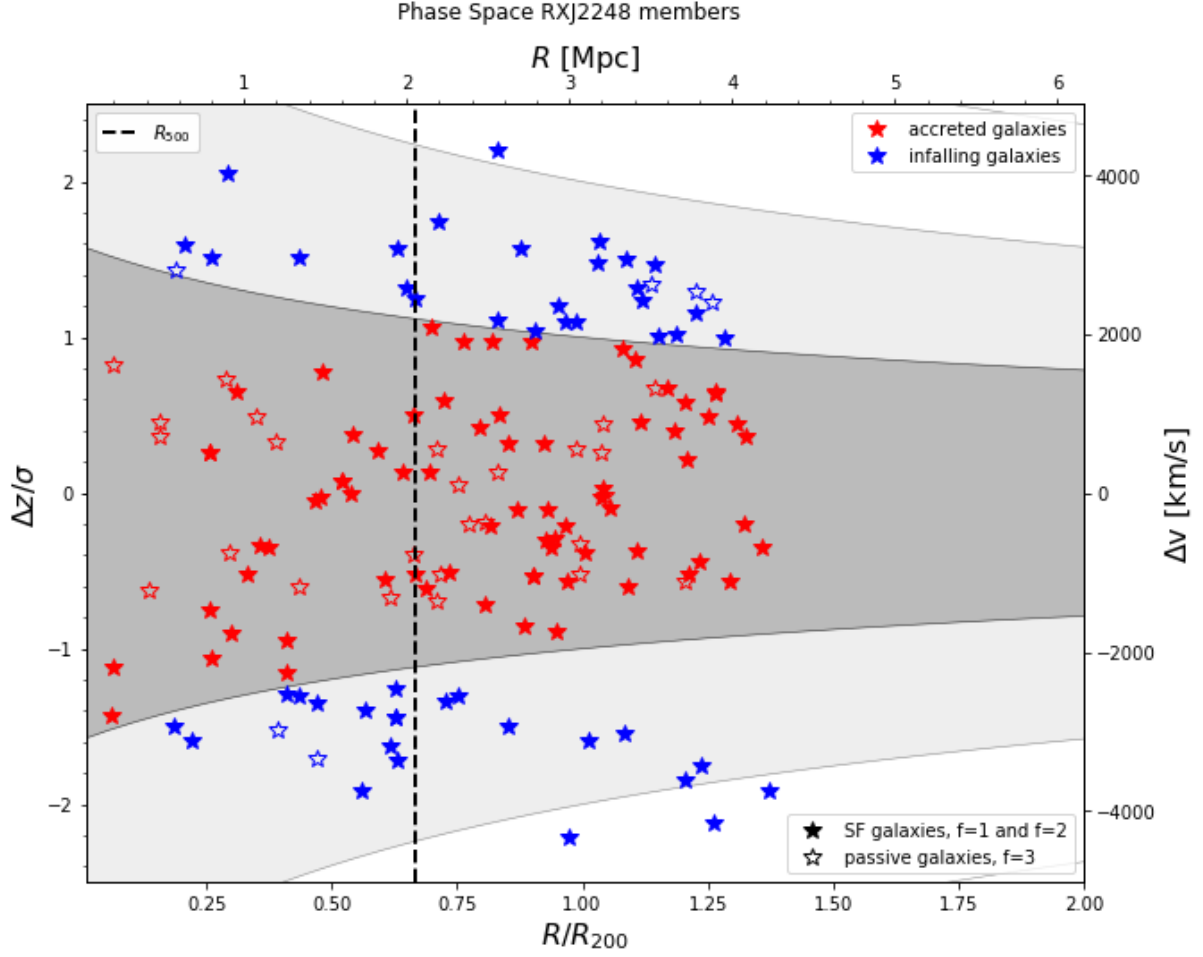


Figure 5.24: Cluster centric radius vs. line-of-sight velocity for the RXJ2248 cluster members. The red dots located within 1σ (dark-grey shaded area) are considered to be accreted and possibly virialised cluster members, which are in dynamical equilibrium with the clusters' potential. The blue symbols located between $2\sigma - 3\sigma$ (light grey shaded area) are classified as infalling galaxies, which have been just recently accreted into the cluster. The filled stars stand for the active cluster galaxies, which show ELs in their spectra and are described either by a quality flag $f=1$ or a quality flag $f=2$. The open stars represent the sample of passive galaxies which show weak/no ELs in their spectra, and which are described by a quality flag $f=3$. The dashed black line stands for R_{500} .

and compare the median (O/H) values between field and cluster galaxies within each of these 2 mass bins. The black lines and diamonds represent the median (O/H) values for accreted cluster galaxies (left) and infalling ones (right), together with the standard error of the mean. The blue lines and diamonds stand for the median (O/H) of field galaxies, together with the errors.

For a better visualisation, fig. 5.26 shows the (O/H) distribution (O3N2 calibration) of field galaxies with $0.3 < z < 0.4$ and cluster members with different accretion histories. The plots from the upper 2 panels show the distribution of the gas phase metallicities for accreted cluster members (black histogram) as compared to the (O/H) distribution of field galaxies (blue histogram) from the low M bin (left) and high M bin (right). The dashed black line represents the median (O/H) value for accreted cluster members in the respective mass bin, while the blue dashed line stands for the median (O/H) value for field galaxies. The plots from the lower 2 panels show the (O/H) distribution of accreted cluster members (black histograms) as compared to the (O/H) distribution of infalling cluster members (blue histograms) from the low M bin (left) and high M bin (right). The dashed black line stands for the median (O/H) value for accreted cluster galaxies and the blue one for the median (O/H) of infalling cluster galaxies. Both galaxies described by a quality flag $f=1$ and $f=2$ are considered.

Based on fig. 5.25 and 5.26, one can notice that at the high-mass end, there seems to be no difference between the median (O/H) of accreted cluster members and the field population, given the uncertainties. The same can be said for the (O/H)s of infalling cluster galaxies and the field galaxies from the high mass end. Both cluster populations have a median (O/H) value, which is by ~ 0.01 dex higher than the median (O/H) of the cluster galaxies, yielding a $\sim 0.34\sigma$ significance. However, at the low mass end an effect can be seen: both accreted and infalling cluster galaxies have more enhanced metallicities than the population of field galaxies. The median (O/H) of the accreted cluster galaxies is by a factor of ~ 0.07 dex higher than the median (O/H) of field galaxies, with a $\sim 1.95\sigma$ significance. The median (O/H) of infalling cluster galaxies is by a factor of ~ 0.075 dex higher than the median (O/H) of the field population, with a $\sim 1.1\sigma$ significance. The (O/H)s of accreted and infalling cluster galaxies from both the low and high mass bin are comparable, given the uncertainties.

In order to further test the metallicity effects observed so far, an additional criterion to the division into accreted/infalling cluster galaxies was assumed. We know that at clustercentric distances lower than R_{500} , due to the high density of the ICM, (mild) ram pressure stripping should be more effective in removing the hot, diffuse halo gas of galaxies, especially if the galaxies have lower masses. Therefore, it is expected that star forming galaxies, which are found at distances $R < R_{500}$, should have more enhanced metallicities than their field counterparts.

Because of this, accreted cluster members were classified according to the phase-space analysis as lying within the 1σ contour of the trumpet shaped caustic profile, and additionally, as lying at distances $R < R_{500}$. Infalling cluster galaxies were characterised according to their location in projected phase space as lying both between the $1\sigma - 2\sigma$ contours of the caustic and within the 1σ contour, but at distances from the cluster centre $R > R_{500}$. The results can be seen in fig. 5.27 and 5.28. Fig. 5.27 depicts the MZR of field galaxies with $0.3 < z < 0.4$ and accreted cluster members on the left-hand side and the MZR of field galaxies and infalling cluster galaxies on the right-hand side. The division between accreted and infalling cluster galaxies was done according to the aforementioned new classification. Oxygen abundances were computed using the O3N2 calibration and all galaxies described by a quality flag $f=1$ and $f=2$ were considered. The symbols are the same as in the previous plots. Fig. 5.28 shows the distribution of the oxygen abundances (O3N2 calibration) of field galaxies and cluster members with different accretion histories. The sample of galaxies was divided into 2 mass bins and the (O/H) distribution of the different populations was compared to each other. The dashed lines in all the plots stand for the median (O/H) value of the respective population, colour coded accordingly. According to fig 5.27 and 5.28, the median (O/H) value of accreted cluster galaxies from the low mass bin is by a factor of 0.065 dex higher than the median (O/H) value of the field population, with a 0.95σ significance. Infalling cluster galaxies also show more enhanced metallicities than the sample of field galaxies. The mean value of the (O/H) of infalling cluster galaxies is by a factor of 0.082 dex higher than that of the field galaxies, with a 1.9σ significance. At the high mass end, both infalling and accreted cluster galaxies show comparable median (O/H) values to the population of field galaxies. Again, we find no distinction between the median (O/H) values of infalling and accreted cluster members.

Based on the four preceding figures, one can conclude the following: the median (O/H)s of accreted and infalling cluster galaxies are very similar at all masses. At the high mass-end, no substantial difference can be observed between the median (O/H) values of field galaxies and cluster members with different accretion histories, given the errors. At the low mass end, however, an effect can be seen: both accreted and infalling cluster galaxies show more enhanced metallicities than their field counterparts, by a factor of ~ 0.07 dex.

The main result of this analysis is the following: regardless of whether accreted/infalling galaxies are classified purely according to their location in projected phase space or with the additional constraint imposed by the location within or beyond R_{500} , the same trends are observed, with both accreted and infalling low mass cluster members ($\log(M/M_{\odot}) < 9.5$) showing more enhanced metallicities than their field counterparts, with a $\sim 1.9\sigma$ significance.

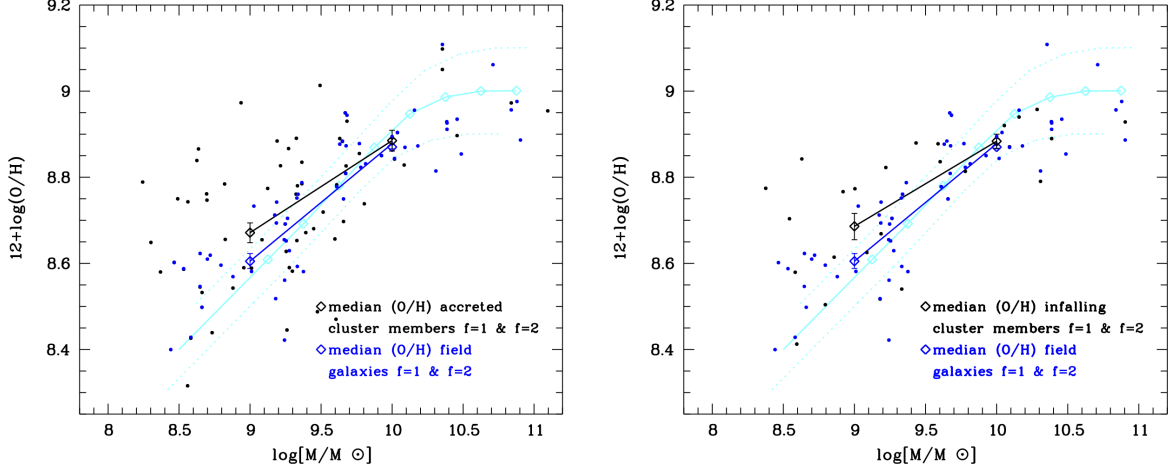


Figure 5.25: MZR for cluster members with different accretion histories and for field galaxies with $0.3 < z < 0.4$, using the **O3N2** calibration of Kewley et. al 2013. The plot on the left-hand side depicts the MZR for field galaxies (blue dots) as compared to the MZR of accreted RXJ2248 cluster members (black dots). The plot on the right-hand side shows the (O/H) comparison between field galaxies and infalling cluster members. For a meaningful comparison, the sample of galaxies was divided into 2 mass bins: $8.3 < \log(M/M_\odot) < 9.5$ and $9.5 < \log(M/M_\odot) < 11$. The median (O/H)s of field and cluster galaxies in each mass bin were compared to each other: the black diamonds stand for the median (O/H) of cluster members with different accretion histories, while the blue ones represent the median (O/H) of field galaxies. The cyan diamonds and curves represent the local SDSS MZR.

In appendix E we compare the median (O/H) values of field galaxies to the median (O/H) values of infalling and accreted cluster members respectively, but here, metallicities were derived using the $[OIII]/H\beta$ calibration. Figures E.1 and E.2 show the (O/H) comparison between field galaxies and accreted / infalling cluster members, as classified according to their location in projected phase space. For fig. E.3 and E.4, we adopt the new classification into accreted/infalling cluster galaxies, by additionally imposing the R_{500} criterion. The same trends are observed in these cases as well.

5.8.2 The fundamental metallicity relation $Z(M, \text{SFR})$ for the RXJ2248 galaxies

As argued in the previous sections, it is clear that there exists a tight correlation between the SFR and the stellar mass of a galaxy (sSFR-M relation), as well as a correlation between the

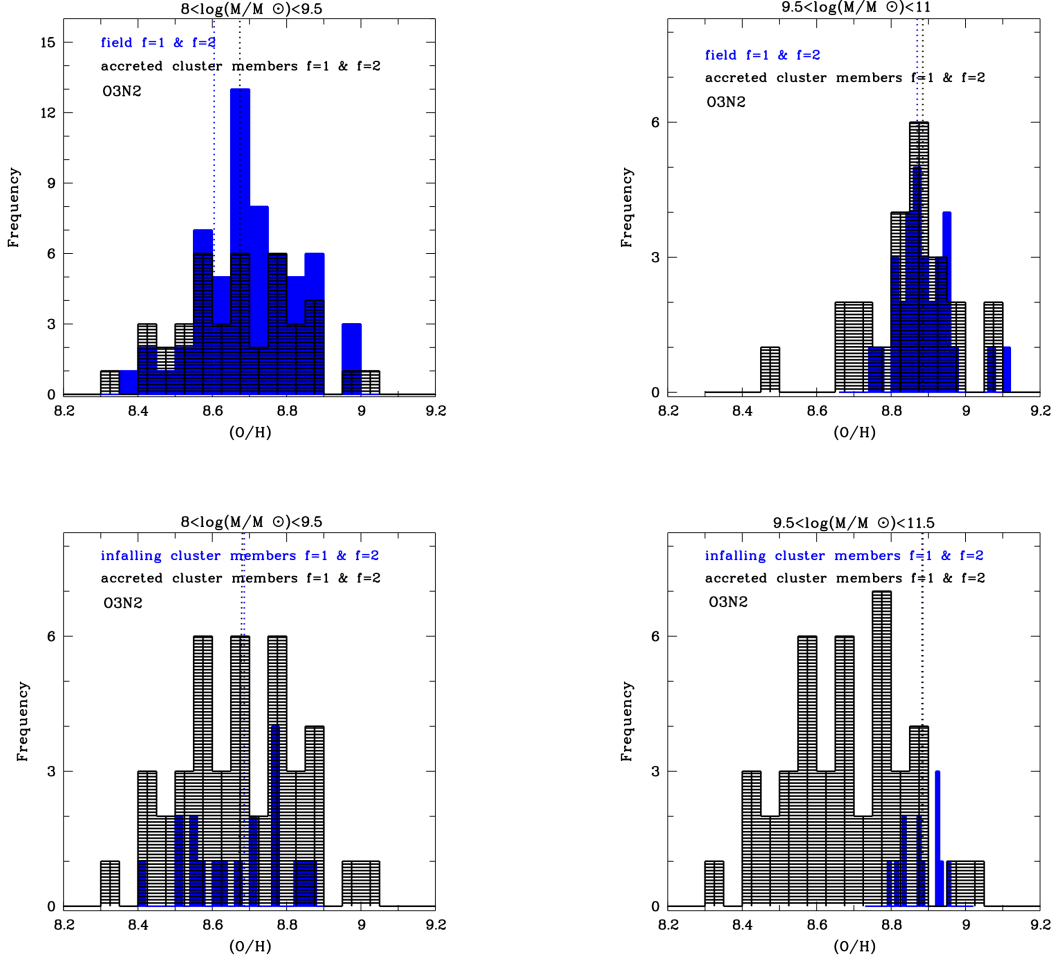


Figure 5.26: (O/H) distribution (**O3N2**) for field galaxies, accreted and infalling cluster members, divided into 2 mass bins. The plots from the upper 2 panels show the distribution of the gas phase metallicities of accreted cluster members (black histogram) as compared to the (O/H) distribution of field galaxies (blue histogram). The graphs from the lower 2 panels show the (O/H) distribution of accreted cluster members (black histograms) as compared to the (O/H) distribution of infalling cluster members (blue histograms). The dashed lines in all plots stand for the median (O/H) values for the respective sample of galaxies, colour coded accordingly.

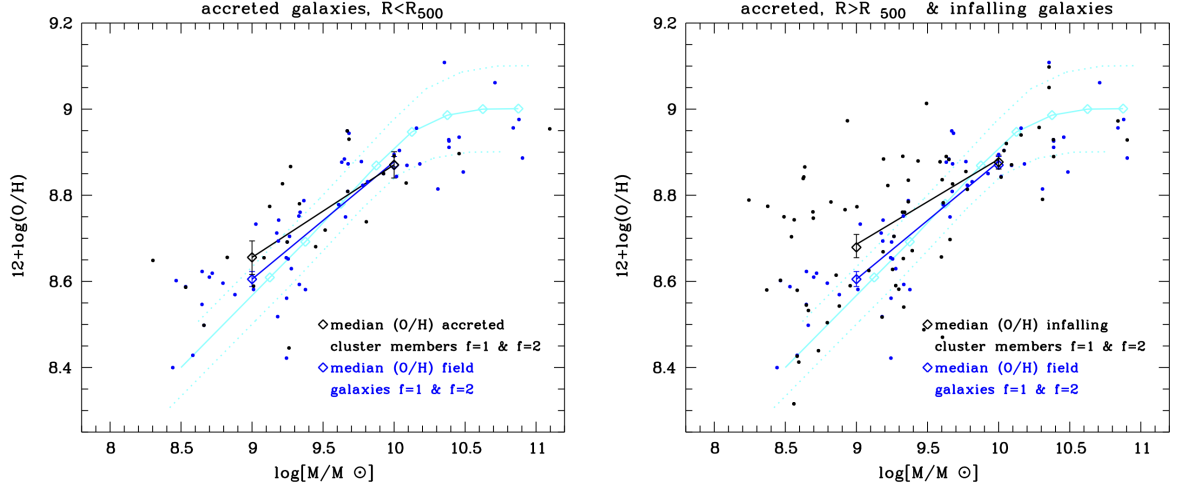


Figure 5.27: MZR for cluster members with different accretion histories and field galaxies with $0.3 < z < 0.4$ using the **O3N2** calibration of Kewley et. al 2013. The plot on the left-hand side depicts the MZR for field galaxies (blue dots) as compared to the MZR of accreted (**within** 1σ **and** $R < R_{500}$) RXJ2248 cluster members (black dots). The plot on the right-hand side shows the (O/H) comparison between field galaxies and infalling cluster members (**within** 1σ **and** $R > R_{500}$ **and between** $1\sigma - 2\sigma$). For a meaningful comparison, the sample of galaxies was divided into 2 mass bins: $8.3 < \log(M/M_{\odot}) < 9.5$ and $9.5 < \log(M/M_{\odot}) < 11$. The median (O/H) values of field and cluster galaxies in each mass bin were compared to each other: the black diamonds stand for the median (O/H) of cluster members with different accretion histories, while the blue ones represent the median (O/H) of field galaxies. The cyan diamonds and curves stand for the local SDSS MZR.

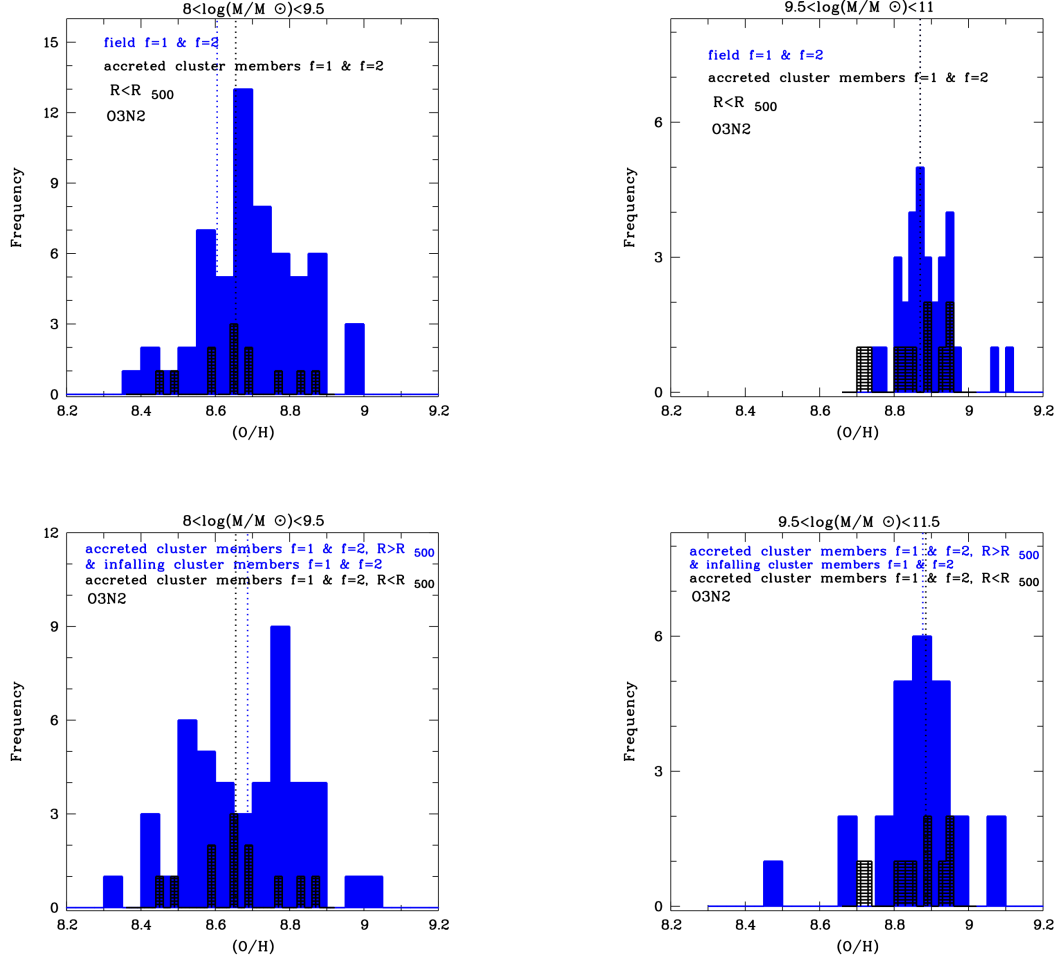


Figure 5.28: (O/H) distribution (**O3N2**) for field galaxies, accreted and infalling cluster members (according to the new classification), divided into 2 mass bins. The plots from the upper 2 panels show the distribution of the gas phase metallicities for accreted cluster members (black histogram) as compared to the (O/H) distribution of field galaxies (blue histogram). The graphs from the lower 2 panels show the (O/H) distribution of accreted cluster members (black histograms) as compared to the (O/H) distribution of infalling cluster members (blue histograms). The dashed lines in all plots stand for the median (O/H) value of the respective sample of galaxies, colour coded accordingly.

gas-phase metallicity of a system and its stellar mass (MZR). Observations have also shown that oxygen abundances anti-correlate with SFRs, especially at low stellar masses, such that at a given mass, galaxies with high SFR will show lower (O/H). This led to the conclusion that the chemical abundance of a galaxy is dependent on both the stellar mass and the SFR, giving rise to the so called "Fundamental Metallicity Relation" $Z(M, \text{SFR})$.

For example Mannucci et al. 2010 assumed that an inflow of gas is the responsible driver for the increase of the SFR and the dilution of the metallicity in order to explain the star formation as a second parameter in the MZR. Lilly et al. 2013 proposed a different explanation to the dependence of Z on M and SFR, by introducing a simple model of galaxy evolution in which the SFR is regulated by the mass of gas present in a galaxy (see section 2.3 for more details).

One of the aims of this thesis is to investigate whether at higher redshift and in a dense cluster environment, the $Z(M, \text{SFR})$ dependence is similar to the one found in the local universe. For this purpose, we calculate the expected (O/H) values from the simple gas regulated model of Lilly et al. 2013 for each galaxy individually, with their respective stellar mass and SFR. This is done by means of equation (40) from Lilly et al. :

$$Z_{eq} = Z_0 + \frac{y}{1 + \lambda(1 - R)^{-1} + \varepsilon^{-1}((1 + \beta - b)M_{star}^{-1} \cdot \text{SFR} + (1 - R)^{-1} \frac{1.2}{t})} \quad (5.56)$$

where Z_{eq} is the equilibrium value for the metallicity, Z_0 the metallicity of the infalling gas, y the yield, λ the mass-loading factor, R the fraction mass returned to ISM, ε the star forming efficiency, β the slope of sSFR- M relation, b a proportionality factor ($\varepsilon \propto M_{star}^b t^{-1}$) and t the time.

Lilly et al. have fitted the SDSS $Z(M, \text{SFR})$ data of Mannucci et al. 2010 with the predicted $Z(M, \text{SFR})$ relation, given in the above equation. The fitted $\varepsilon(M)$ returns a gas depletion timescale, which is consistent with observations. The returned values of the fitted mass-loading factor of the wind λ are also consistent with observations, even though they show a steep mass dependence, which can be traced back to the strong curvature of the MZR of the Mannucci et al. 2010 data. Table 5.4 shows the returned values from the fits to the SDSS data of Mannucci et al., for the different parameters of the gas-regulating model. The values for the parameters of this simple model were then substituted in equation 5.56 by considering 2 cases: a primordial gas inflow with $Z_0/y = 0$ and a metal rich gas inflow for $Z_0/y = 0.1$. It is also worth mentioning that equation 5.56 is specially designed for a Chabrier IMF [8]. Because of this, we need to divide our Salpeter IMF stellar masses by a factor of $f=1.7$, which was found by Pozzetti et al. (2007) to be the systematic offset in the masses derived with the two different IMFs [36]. After calculating the predicted (O/H) value for each individual galaxy in our sample for the 2 different scenarios (metal rich and primordial gas inflow), we compare these expected (O/H)s

to the observed (O/H)s, which were derived through the 3 metallicity calibrations described in section 5.4.1

Fig. 5.29 displays the difference between the measured (O/H)s for the RXJ2249 cluster galaxies, using the O3N2 metallicity calibration, and the expected (O/H) values from the FMR expectation of Lilly et al. 2013 (equation 5.56), for the two different scenarios: a metal enriched gas inflow $Z_0/y = 0.1$ (filled circles) and a primordial gas inflow $Z_0/y = 0$ (open circles). It is also worth considering that recent studies of blue (Bresolin et al. 2016) and red supergiants (Davies et al. 2017) have demonstrated that the metallicity calibration based on strong emission line ratios, yielding the most accurate metallicities is the O3N2 calibration, which was used throughout this study. Therefore, one should concentrate more on the difference between the theoretical (O/H)s and observed (O/H)s obtained using this method. The colour codes of the plot from the left-hand side denote the different quality flags assigned to the spectra: black, blue and red represent the galaxies described by quality flags $f=1$, $f=2$, and $f=3$ respectively. The panels on the right-hand side show the difference between measured and predicted (O/H)s, but only for the galaxies selected for the metallicity study, as described in section 4.3.1.

Fig. 5.30 shows the same as plot 5.29, but in this case, both $f=1$ and $f=2$ galaxies are considered. For a better visualisation, the median values for the difference in (O/H) between measurements and predictions are plotted as a reference (big open/filled circles), for 2 mass bins: $8.3 < \log(M/M_\odot) < 9.5$ and $9.5 < \log(M/M_\odot) < 11$.

In appendix F.1 we show the difference between measured and predicted (O/H)s, when using the other two metallicity calibrations derived by Maier et al. 2016, see fig. F.1 and fig. F.2.

The main results of this section can be summarised as follows: the RXJ2248 cluster galaxies with $9.5 < \log(M/M_\odot) < 11$ have (O/H) values which are in accordance with the model expectations (within ~ 0.2 dex), given the errors of the (O/H) computation. The (O/H)s of high mass cluster galaxies, which were computed through the O3N2 method, are the most consistent to the predicted (O/H) values of the gas regulated model. For the high mass end, no substantial disparity can be seen in the difference between measured and predicted (O/H)s when considering a metal enriched or pristine gas inflow. However, the pristine gas inflow model seems to be the preferred one.

At the low mass end, galaxies with $8.3 < \log(M/M_\odot) < 9.5$ deviate systematically from the predictions of the FMR, regardless of the metallicity calibration used, showing metallicity values up to three to four times higher than predicted. The galaxies in the low mass end seem to be in better agreement with the models which assume an inflow of enriched gas. These results are consistent to the findings of Maier et al. 2016 and Maier et al. 2019, who studied the

Fits of Equation 40 to observational data of Mannucci et al (2010) SDSS $Z(m_{star}, SFR)$					
Z_0/y	$\log y^b$	λ_{10}	a	$\frac{1}{\varepsilon_{10}}$ Gyr	b
[0.00]	9.02	$0.25_{pm0.02}$	-0.81 ± 0.03	2.4 ± 0.2	0.28 ± 0.03
[0.03]	9.00	0.29 ± 0.03	-0.79 ± 0.03	2.8 ± 0.2	0.32 ± 0.03
[0.10]	8.98	0.40 ± 0.04	-0.77 ± 0.03	3.8 ± 0.3	0.41 ± 0.04

Table 5.4: This table shows the Lilly et al. 2013 fits of their equation (40), corresponding to equation 5.56 from this work, to the Mannucci et al (2010) SDSS $Z(m_{star}, SFR)$ data [8].

environmental effect on gas regulation within cluster galaxies. The authors of this paper found that low-mass cluster galaxies have 2-3 times higher metallicities than predicted by the models which assume an inflow of pristine gas, indicating that a strangulation scenario, in which the gas inflow is cut off, can explain the enhanced (O/H)s [15, 63]. An explanation for these observed metallicity effects will be given in the sections that follow.

5.8.3 The fundamental metallicity relation $Z(M, SFR)$ for the comparison sample of field galaxies

Of interest for this work are the field galaxies with $0.3 < z < 0.4$, described by a quality flag $f=1$, which were chosen as the comparison sample to the RXJ2248 cluster. Fig. 5.31 shows the difference between the measured (O/H)s for field galaxies with $0.3 < z < 0.4$, using the metallicity calibration based on the O3N2 index and the expected (O/H)s from the formulations of Lilly et al. 2013 for different infall metallicities Z_0 relative to the yield y , $Z_0/y = 0.1$ (metal enriched gas inflow, filled circles) and $Z_0/y = 0$ (primordial gas inflow, open circles). Fig. 5.32 shows the same as fig. 5.31, but in addition, the median values of the difference between measured (O/H) and predicted (O/H) (assuming both the models with pristine and enriched gas inflow) are plotted (large open and filled circles respectively), together with the respective errors. All galaxies described by a quality flag $f=1$ are considered.

Based on these two figures, one can conclude the following: low mass galaxies with $8.3 < \log(M/M_\odot) < 9.5$ show predominantly higher gas-phase metallicities than predicted, being in accordance to both models of pristine and enriched gas inflow. However, the differences between observed and predicted (O/H) values are not as extreme as in the case of cluster galaxies. On the other hand, field galaxies at the high mass end with $9.5 < \log(M/M_\odot) < 11$ have (O/H)s which are comparable to the predictions of the FMR. These massive galaxies seem to be better

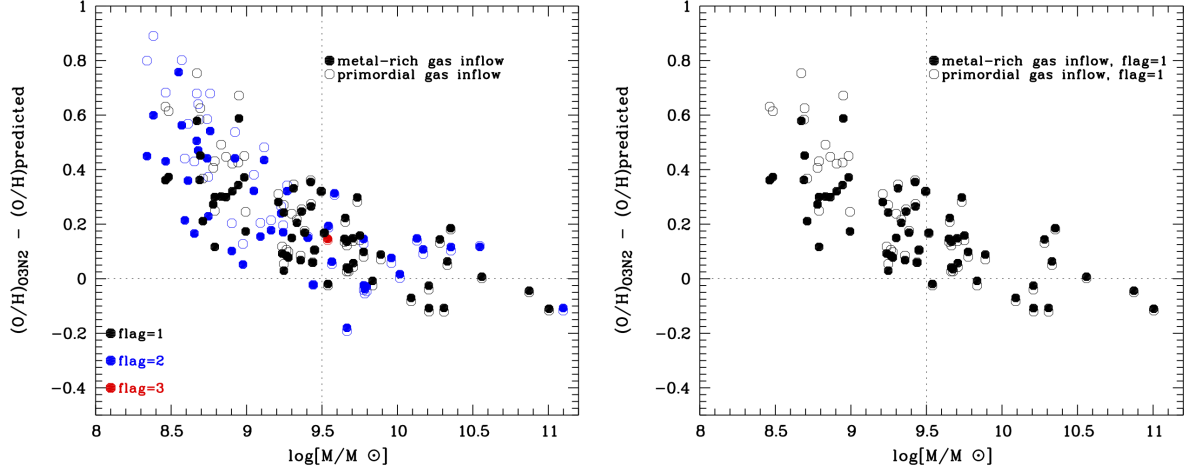


Figure 5.29: Difference between the measured (O/H) s for the RXJ2249 cluster galaxies, using the O3N2 metallicity calibration, and the expected (O/H) s from the formulations of Lilly et al. 2013 for different infall metallicities Z_0 relative to the yield y , $Z_0/y = 0.1$ (metal enriched gas inflow, filled circles) and $Z_0/y = 0$ (primordial gas inflow, open circles). The panel from the left-hand side shows the difference between the measured and predicted oxygen abundances for the whole sample of RXJ2248 cluster members with available measurements of the emission lines $[OIII]$, $H\beta$, $[NII]$ and $H\alpha$. The colour codes stand for the different quality flags assigned to the spectra: black, blue and red represent the galaxies described by quality flags $f=1$, $f=2$, and $f=3$ respectively. The panel on the right-hand side also shows the difference between measured and predicted (O/H) s, but only for the cluster members described by a quality flag $f=1$.

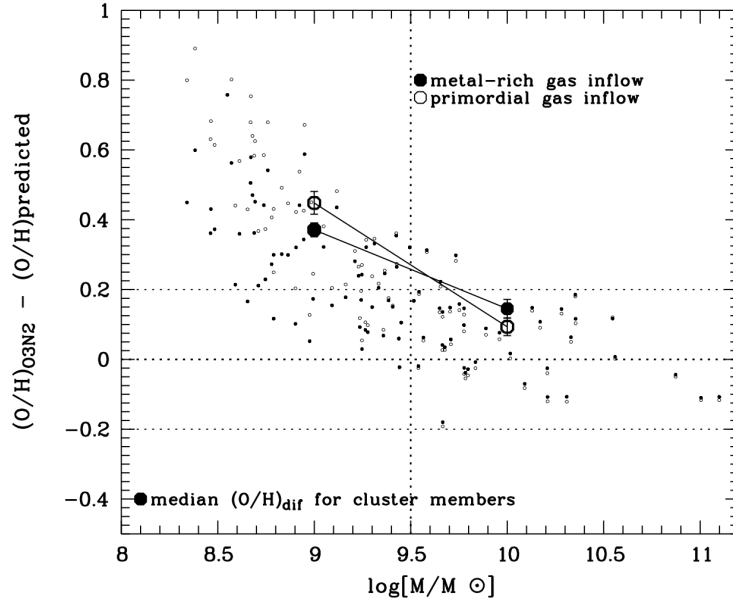


Figure 5.30: Difference between the measured (O/H) s for RXJ2248 cluster galaxies, using the O3N2 metallicity calibration, and the expected (O/H) s from the formulations of Lilly et al. 2013 for different infall metallicities Z_0 relative to the yield y , $Z_0/y = 0.1$ (metal enriched gas inflow, filled circles) and $Z_0/y = 0$ (primordial gas inflow, open circles). The median values for the difference in (O/H) between measurements and predictions are plotted as a reference (big open/filled circles), for 2 mass bins: $8.3 < \log(M/M_{\odot}) < 9.5$ and $9.5 < \log(M/M_{\odot}) < 11$.

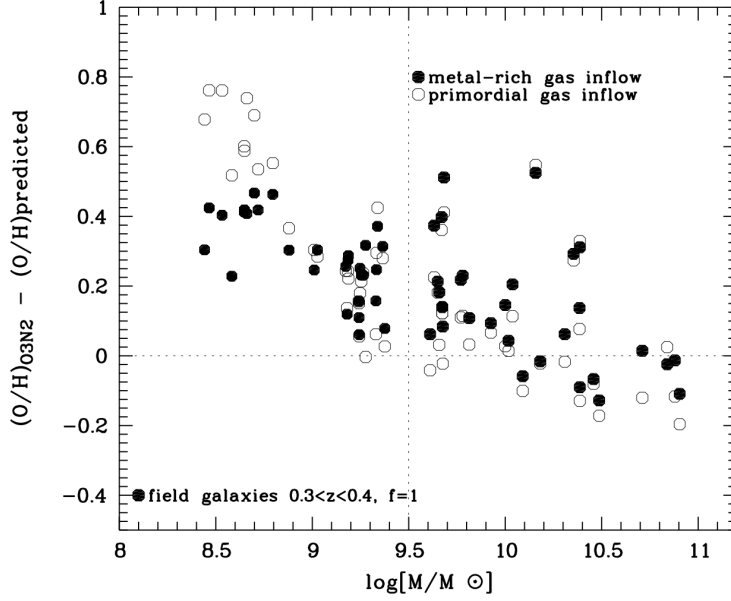


Figure 5.31: Difference between the measured (O/H)s for the comparison sample of field galaxies with $0.3 < z < 0.4$, using the metallicity calibration based on the O3N2 index and the expected (O/H)s from the formulations of Lilly et al. 2013 for different infall metallicities Z_0 relative to the yield y , $Z_0/y = 0.1$ (metal enriched gas inflow, filled circles) and $Z_0/y = 0$ (primordial gas inflow, open circles).

in accordance with models of pristine gas inflow.

In appendix F.2 we show the difference between the (O/H)s derived using the $[OIII]/H\beta$ calibration and the predicted (O/H)s from the gas-regulated model for the comparison sample of field galaxies, see fig. F.3. In addition, we also show the FMR for the sample of field galaxies from the low redshift bin $0.01 < z < 0.33$ and high redshift bin $0.36 < z < 0.9$, see fig. F.4 and F.5. We compute the difference between measured (O/H)s using both the O3N2 and the $[OIII]/H\beta$ metallicity calibration and the predicted (O/H)s of the bathtub model.

5.8.4 FMR $Z(M, SFR)$ comparison between field galaxies and cluster members at different cluster centric radii

Fig. 5.33 shows the difference between measured (O/H)s (O3N2 calibration) and the predicted (O/H)s from the formulations of Lilly et al. 2013 for different metallicities of the infalling gas - metal enriched gas inflow (filled circles) and primordial gas inflow (open circles) - for field galaxies with $0.3 < z < 0.4$ and for cluster galaxies with different accretion histories. The upper two panels show the median value of the difference between the measured and the expected (O/H)s

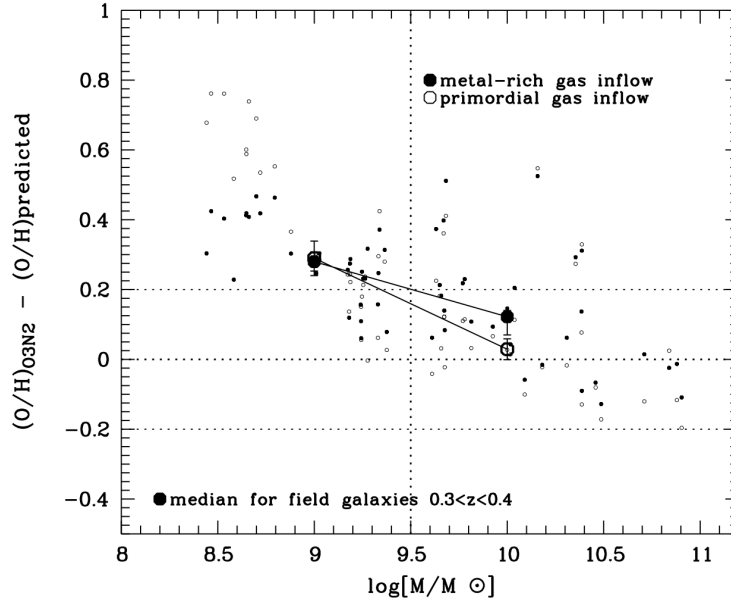


Figure 5.32: Difference between the measured (O/H) s for field galaxies with $0.3 < z < 0.4$, using the O3N2 metallicity calibration, and the expected (O/H) s from the formulations of Lilly et al. 2013 for different infall metallicities Z_0 relative to the yield y , $Z_0/y = 0.1$ (metal enriched gas inflow, filled circles) and $Z_0/y = 0$ (primordial gas inflow, open circles). The median values for the difference in (O/H) between measurements and predictions are plotted as a reference (big open/filled circles), for 2 mass bins: $8.3 < \log(M/M_{\odot}) < 9.5$ and $9.5 < \log(M/M_{\odot}) < 11$.

for field galaxies in blue and for accreted cluster galaxies (within the 1σ contour of the caustic profile in the phase space diagram) in black. The lower two panels depict the median value of the difference between measured and predicted (O/H)s of field galaxies in blue and infalling cluster members (between the $1\sigma - 2\sigma$ contours of the caustic profile) in black. In the low mass bin ($8.3 < \log(M/M_\odot) < 9.5$), field galaxies are more in agreement to the model predictions (assuming both primordial and metal rich gas inflow) than accreted and infalling cluster members, which show higher (O/H)s than predicted. When assuming a metal enriched gas inflow, accreted and infalling cluster galaxies show higher (O/H)s than predicted, by a factor of ~ 0.4 dex. When using the model with primordial gas inflow, both cluster populations show (O/H) values which are higher by a factor of ~ 0.5 dex than predicted by the gas regulated model. The cluster galaxies are, thus, more in accordance with models which assume a metal enriched gas inflow. At the high mass end ($8.3 < \log(M/M_\odot) < 9.5$), however, all populations seem to be in agreement to the model predictions, assuming both metal enriched and primordial gas inflow. This observed metallicity effect suggests that low mass galaxies are more prone to environmental effects when accreted into the cluster, due to their shallow gravitational potential.

These findings are in accordance to the predictions of Peng et al. 2014, who studied the dependence of the MZR of SDSS galaxies on the environment, with regards to both the over-density and central/satellite dichotomy. They find that, for a given stellar mass, there is a fairly strong dependence of the gas phase metallicity on the density of the ICM, with high metallicity galaxies (satellites) residing in denser regions than their low metallicity analogues. The authors proposed that the inflow of gas into the halo of a galaxy residing in a dense cluster environment should get progressively more metal-enriched (meaning that Z_0 becomes higher), producing thus enhanced metallicities for low mass cluster galaxies, as compared to their field counterparts. They also test their results by applying the gas-regulator model of Lilly et al. 2013 and find a good accordance with the models with metal rich gas inflow. However, no physical mechanism was proposed to explain how a metal enriched gas inflow can still occur for galaxies residing in dense cluster environments. The authors of this paper have, however, proposed an alternative mechanism which can lead to the same effects of enhanced metallicities in low mass cluster galaxies, namely strangulation. This scenario is however not further elaborated, due to the fact that they find that the sSFRs of cluster and field galaxies are similar [71]. The same trend is observed for our investigated sample of galaxies too.

Strangulation/starvation is a mechanism that causes the removal of the diffuse hot gas reservoir confined in the galaxy halo, while the gas-disk is left unperturbed. This means that star formation can actually continue until the internal gas-reservoir is used up. Therefore, after the

removal of the hot halo gas, there will be a time delay until the system will undergo star formation quenching. Because of this, even if the SFRs of cluster and field galaxies are comparable, that does not mean that strangulation should be excluded as a mechanism which explains the observed metallicity effects.

In a more recent publication, based on a sample of local SDSS galaxies, Peng et al. 2015 found that for low mass cluster galaxies with $\log(M/M_\odot) < 10.2$, the stellar metallicity is slightly higher than that of central galaxies, implying that low mass galaxies are more easily affected by the environment in which they reside and that such environmental effects are responsible for the stopping the gas inflow [72]. In the section that follows, we discuss whether strangulation is a plausible mechanism to explain the metallicities of cluster galaxies.

5.8.5 Discussion: environmental effects

In a recent study, Haines et al. 2013 investigated a large sample of LoCuSS cluster galaxies of intermediate redshifts in terms of the evolution of their star formation activity, and found that massive, actively star forming galaxies, when accreted into high mass clusters, are slowly quenched. Infalling spiral galaxies will lose their gas reservoirs due to (mild) ram pressure stripping as they interact with the hot ICM and this will result in a gradual decrease in their star formation rates. The authors found that the SFRs of cluster galaxies decline exponentially on time-scales between 0.7-2.0 Gyr, and concluded that mechanisms such as ram pressure stripping and strangulation are responsible for quenching star formation on such long time scales.[72].

This is in accordance with other recent publications such as Cantale et al. 2016, who investigated the colours of late-type spirals from ten EDisCS clusters of intermediate z , and their results suggest that galaxies are able to continue forming stars for some significant period of time, up to 5 Gyr, after being accreted into clusters.

For eg. Jaffé et al. 2015 studied the effects of ram-pressure on stripping the HI gas from intermediate z cluster galaxies from the BUDHIES survey, also found out that ram-pressure plays an important role in removing the gaseous reservoir of galaxies, and that this can happen during the first infall into the cluster. However, these galaxies are still able to continue to form stars from the remaining gas disk. They also conclude that the gas stripping will occur once the galaxies have approached the dense ICM core and/or gained enough velocity to cross the stripping area in phase-space, defined as the small clustercentric distances and/or high line-of-sight velocities. After this stripping process, galaxies are expected to "oscillate" in phase-space, until they accumulate towards the clusters' core due to dynamical friction. They inferred this to be a fairly long process, lasting up to > 4 Gyr. During this time, it is expected that the galaxies

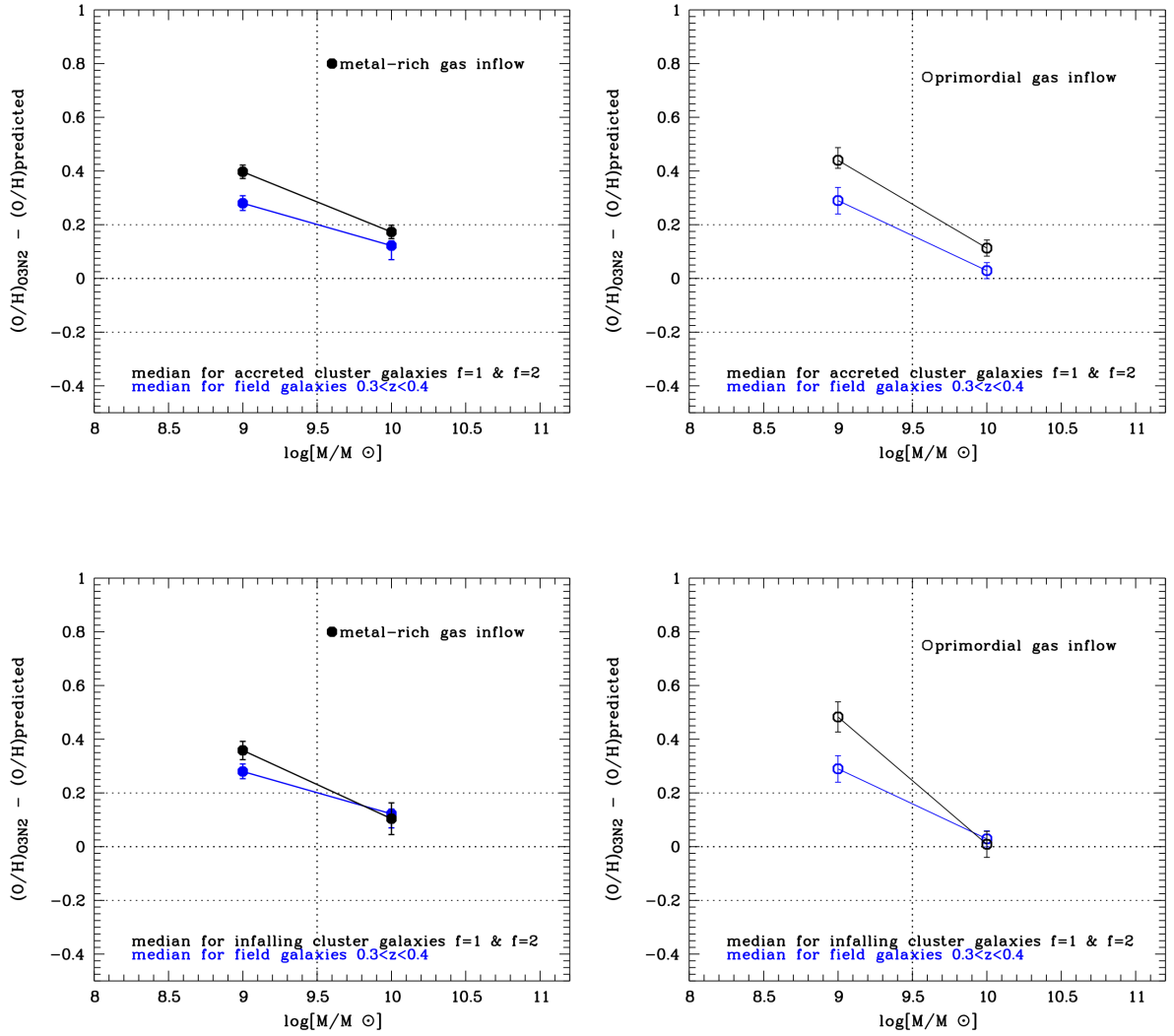


Figure 5.33: Difference between the measured (O/H) s using the O3N2 metallicity calibration and the expected (O/H) s from the formulations of Lilly et al. 2013 for different inflow metallicities Z_0 relative to the yield y , $Z_0/y = 0.1$ (metal enriched gas inflow, filled circles) and $Z_0/y = 0$ (primordial gas inflow, open circles). The upper panels show the median value of the difference between measured and predicted (O/H) s of field galaxies (blue) and accreted cluster members (black), assuming a model with primordial gas inflow (left) and metal rich gas inflow (right). The lower two panels depict the median value of the difference between measured and predicted (O/H) s of field galaxies (blue) and infalling cluster members (black), assuming a model with primordial gas inflow (left) and metal rich gas inflow (right).

exhaust their gas reservoirs, which will, in turn, cause the quenching of star formation[74].

Gott and Gunn et al. 1972 demonstrated that gas can be removed from infalling cluster galaxies if the ram pressure exceeds the restoring force per unit area (i.e. gravitational restoring force) exerted by the galaxy. The ram pressure exerted by the ICM can be expressed as:

$$P_{ram} = \rho_{ICM} \cdot v^2 \quad (5.57)$$

where ρ_{ICM} stands for the ICM density, and v for the velocity of the galaxy. If the galaxy is a spiral, the material will be held in the plane by a force per unit area given by:

$$P_{restoring} = 2\pi G \Sigma_* \Sigma_{ISM} \quad (5.58)$$

with Σ_* the star surface density and Σ_{ISM} the gas surface density. Thus, the gas will be stripped from the galaxy if [75] :

$$\rho_{ICM} > \frac{2\pi G \Sigma_* \Sigma_{ISM}}{v^2} \quad (5.59)$$

For eg., Bahé et al. 2013 studied the environmental effects which lead to star formation quenching in cluster galaxies by means of a suite of high-resolution cosmological hydrodynamic simulations. The authors of this paper have analysed galaxies from simulated groups and clusters with a wide range of stellar masses, in order to compute the density of the ICM and the ram pressure in clusters. This allowed them to investigate how effective ram pressure can strip away the gas reservoirs of cluster galaxies. They find a systematic reduction of both the hot and cold gas component and a decline in the star forming fraction of galaxies with decreasing clustercentric distance. These trends were observed as far out as $\sim 5 \cdot R_{200}$ from the cluster centre. The observed radial trends in terms of both star formation and cold gas fraction are explained by galaxies passing the first pericentre (overshooting), meaning that the ram pressure is sufficient to strip off the gas, and also by galaxies having been pre-processed in infalling groups (out to $\sim 2 - 3 \cdot R_{200}$). However, for low mass galaxies, the radial trends are observed even further out and even for galaxies which were not 'pre-processed' in groups or which are falling for the first time into the cluster. For the hot gas component, the observed trends cannot be purely explained by 'pre-processing' and overshooting, implying that the hot gas must be removed at larger clustercentric radii due to hydrodynamical interactions between the ISM of the galaxy and the IGM. For massive clusters with $M \sim 10^{15} M_\odot$ (similar to the mass of the RXJ2248 cluster), Bahé et al. estimated the following range for the ram pressure:

$$P_{ram} \sim 3 \cdot 10^{-14} N/m^2 - 10^{-12} N/m^2 \quad (5.60)$$

near R_{200} for $\sim 90\%$ of the simulated galaxies (figure 9. in Bahé et al. 2013).

For massive galaxies with $9 < \log(M/M_\odot) < 10$, they derived the following typical values for

the restoring pressure of the cold gas and warm gas respectively :

$$P_{restoring, cold\ gas} = 3 \cdot 10^{-12} N/m^2 - 10^{-11} N/m^2 \quad (5.61)$$

$$P_{restoring, hot\ gas} = 3 \cdot 10^{-14} N/m^2 \quad (5.62)$$

The reason for this difference in the restoring pressures of hot/cold gas is due to the fact that cold gas is denser, and sits much closer to the galactic centre, being thus more strongly gravitationally bound.

When comparing the restoring pressure to the ram pressure near R_{200} , it is clear that the latter one is too low to strip cold gas in massive galaxies, but just sufficiently high to strip the hot gas from lower mass systems. As the hot halo gas is less tightly gravitationally bound (by c.a. two orders of magnitudes) than the cold gas component, ram pressure can strip it more efficiently: even the most massive galaxies can be affected out to $\sim 2 - 3R_{200}$ in clusters and most low mass systems are subject to sufficient ram pressure even at large clustercentric distances of $5 \cdot R_{200}$. The removal of the hot gas component at $R > R_{200}$ due to mild ram pressure stripping (i.e. strangulation) will lead to a delayed decrease in the SFR of the system, as the cold gas disk remains unperturbed, and thus stars can continuously form until the gas reservoir is consumed. Strangulation is a slow mechanism which at first, will not affect the SFR of the galaxy. However, as galaxies continue to move through the hot ICM towards the dense cluster centre, the ram pressure will increase to values $P_{ram} > 3 \cdot 10^{-12} N/m^2$, which are comparable to the restoring pressure of the cold gas, meaning that the cold-gas component can also be stripped away. The removal of the cold gas disk of a galaxy will lead to a rapid phase of complete star formation quenching[76].

These findings are in accordance with another recent publication by Roberts et al. 2019, who explored the influence of the dense ICM on quenching cluster satellite galaxies, based on a large sample of SDSS galaxies with available Chandra X-ray observations. The authors concluded that the quenched fractions of intermediate- and high mass cluster galaxies show a moderate but continuous increase with ICM density, whereas the quenched fraction of low mass galaxies has a broken power law dependence on the ICM density. The quenched fraction for low mass galaxies at high ICM density can be described by a simple analytic model of ram pressure stripping. The results of this study are consistent with a slow (strangulation) then rapid (RPS) process of SF quenching in cluster satellites [78].

Once a galaxy's gas supply is cut off due to strangulation, the system can be described by a "closed-box model". For eg. Maier et al. 2006 explored which region of the parameter space could reproduce the constraints inflicted by the metallicity-luminosity relation of both local and high z galaxies, based on a large grid of Pgase2 models. They analysed different models in which

the gas supplies of the model galaxies are cut off, and these systems continue to form stars in a "closed-box" like environment. The tracks of these closed box models have demonstrated that after the gas inflow is suppressed and eventually stopped, galaxies will enhance their gas phase metallicities by a factor of ~ 0.2 dex on time scales of ~ 1 Gyr [79]. According to these findings, infalling cluster galaxies, which experience strangulation, can enhance their metallicities while travelling towards the central parts of the cluster.

The observational results of this work reveal enhanced metallicities for cluster galaxies, as compared to the population of field galaxies at similar redshifts. As the investigated RXJ2248 cluster galaxies extend out to a maxim distance from the cluster centre of $\sim 1.25R_{200}$, mild ram pressure stripping has probably already affected the hot halo gas of these systems. Of course, this mechanism is expected to be more efficient in removing the hot gas of low mass galaxies, due to their shallower gravitational potential. Because of this, no significant difference can be observed in the (O/H)s between infalling (high l.o.s. velocity systems) and accreted cluster members (low l.o.s. velocity systems) at all stellar masses, as both of these populations reside, in projection, close to the cluster core. However, both infalling and accreted cluster galaxies show more enhanced metallicities than their field counterparts, especially at the low mass end, by a $\sim 2.4\sigma$ significance. This indicates that, when accreted, cluster galaxies (especially low mass ones) are more prone to be affected by strangulation, and therefore, they will increase their metallicities while moving through the hot ICM towards the central regions of the cluster. The observed metallicity effect is indeed weak, but this is also related to the fact that a low number of galaxies was used for the statistics. To conclude, strangulation can be considered to be a plausible mechanism to explain the observed metallicity effects in cluster galaxies of intermediate redshifts. The results of this work are consistent with the findings of both Maier et al. 2016 and Maier et al. 2018, who also observed enhanced metallicities for low mass cluster galaxies, in comparison to the population of field galaxies.

Chapter 6

Summary and conclusion

The aim of this master thesis is to investigate the environmental effects on gas regulation within galaxies based on a large sample of CLASH-VLT VIMOS galaxy spectra with available WFI photometry. We study the impact that the environment has on the $Z(M, \text{SFR})$ relation of both CLASH RXJ2248 cluster members at $z_{\text{med}} = 0.348$ and of field galaxies with $0.01 < z < 0.9$. The main results can be summarised as follows:

1. **Colour-Magnitude and Colour-Mass:** The vast majority of the investigated cluster galaxies populate the blue cloud in the colour-magnitude diagram, with a lower fraction transitioning the green valley towards the red sequence, see fig. 5.1. The same can be said for the field population. Galaxies with high B-R values are usually characterised by a quality-flag $f=3$, and show weak or no emission lines in their spectra.
2. **SF galaxies and AGNs:** We have used different diagnostic diagrams based on emission-line ratios in order to differentiate whether the main source of ionisation within galaxies comes from the stellar component or from an AGN. Both field and cluster SF-galaxies are not dominated by AGNs, and they follow the SF-sequence in the BPT/WHAN/Lamareille diagram. Only a low number of galaxies were classified as AGNs and excluded from the metallicity study.
3. **sSFR-M relation:** SFRs were computed from the luminosity of the $H\alpha$ line for galaxies with $z < 0.4$ and from the luminosity of the [OII] line for galaxies with $z > 0.4$. Both field and cluster galaxies can be classified as SF "Main Sequence" galaxies, with just a lower fraction of galaxies classified as starburst or passive systems. Field and cluster galaxies show a similar sSFR-M and we therefore concluded that this relation seems to be rather independent of whether the galaxies populate the field or cluster, see fig. 5.20. These observational findings are in accordance with Maier et al. 2016 and Maier et al. 2018, who

also found a similar sSFR-M for cluster and field galaxies.

4. **MZR:** Gas phase metallicities were computed using 3 empirically calibrated metallicity estimators: the O3N2 calibration by Kewley et. al 2013, the $[OIII]/H\beta$ and the $[NII]/H\alpha$ line ratio calibrations derived by Maier et al. 2016. Both field and cluster galaxies follow the MZR of local SDSS galaxies, with an offset of low mass galaxies ($8.3 < \log(M/M_\odot) < 9.5$) towards higher metallicities than the local MZR. High mass cluster and field galaxies ($9.5 < \log(M/M_\odot) < 11$) have comparable (O/H)s, while at the low mass end, cluster galaxies show more enhanced metallicities than their field counterparts, by ~ 0.05 dex, yielding a $\sim 1.1\sigma$ significance, see fig. 5.21.
5. **Phase-Space:** The cluster membership of galaxies was tested by means of a phase-space diagram (clustercentric radius vs. line of sight velocity), by implementing the mass model of Carlberg et al. 1997, see fig. 5.22. Galaxies which fall between the 1σ contour of the trumpet-shaped caustic profile, showing low l.o.s. velocities, can be classified as accreted galaxies, which possibly form the virialised population. Galaxies located between the $2\sigma - 3\sigma$ contours of the caustic, showing higher l.o.s. velocities up to $v \sim 10000 \text{ km/s}$, are classified as infalling galaxies which have been just recently accreted into the cluster. Galaxies located between the $3\sigma - 6\sigma$ contours form the near-field population, while galaxies which fall beyond the 6σ contour of the caustic profile are classified as far-field galaxies. In projected phase-space, all cluster galaxies are located close to the cluster centre, within $2R_{200}$.

6. Tentative evidence for strangulation

- (a) **(O/H) comparison between field and cluster galaxies at different cluster-centric radii:** At the high mass end ($9.5 < \log(M/M_\odot) < 11$), there seems to be no difference between the (O/H)s of accreted and infalling cluster members, and their field counterparts. At a low mass end ($8.3 < \log(M/M_\odot) < 9.5$), both accreted and infalling cluster galaxies show more enhanced metallicities than the population of field galaxies. The median (O/H) of the accreted cluster galaxies is by a factor of ~ 0.07 dex higher than the median (O/H) of field galaxies, with a $\sim 1.95\sigma$ significance. The median (O/H) of infalling cluster galaxies is by a factor of ~ 0.075 dex higher than the median (O/H) of the field population, with a $\sim 1.1\sigma$ significance. The MZR of both accreted and infalling cluster galaxies are, however, comparable over the whole mass range, see fig. 5.25. This can be explained by the fact that the sample of cluster galaxies resides, in projection, close to the cluster core, meaning that cluster specific

processes, such as ram pressure stripping, have probably affected the hot halo gas of these galaxies.

- (b) **FMR:** In the high mass bin, the (O/H)s of both accreted and infalling cluster members, as well as those of the comparison sample of field galaxies, seem to be in accordance with the expectations of the FMR of Lilly et al. 2013, when assuming both a model with metal enriched gas inflow, and a model with primordial gas inflow. At the low mass end, however, the measured (O/H)s of field galaxies seem to be more in accordance with the expected (O/H)s from the gas-regulated model, than the (O/H)s of cluster galaxies. The metallicities of both accreted and infalling cluster galaxies deviate systematically from the predicted values, by a factor of ~ 0.4 dex. In the low mass range, all galaxies seem to be in better agreement with the models which assume a metal rich gas inflow, see fig. 5.33. This high discrepancy between observed and predicted (O/H)s indicates that a strangulation scenario, in which the gas inflow has stopped, is a plausible mechanism to account for the enhanced metallicities. These results are consistent to the findings of Maier et al. 2016 and Maier et al. 2018, who investigated the FMR expectation of Lilly et al. 2013 based on other intermediate z clusters.
- (c) Different recent studies have shown that, when accreted into a cluster, galaxies are slowly quenched due to hydrodynamical interactions between the ISM and the hot ICM. Strangulation is expected to be more efficient in removing the hot gaseous component of low mass galaxies, as they have shallower gravitational potential wells. This stripping mechanism will, however, leave the cold gas component unperturbed, meaning that SFR can still occur, until the gas-disk is exhausted. Bahé et al. 2013 have demonstrated, based on a suite of hydrodynamical simulations, that the ram pressure is sufficiently high to strip the hot gas component of both high and low mass cluster galaxies, even at distances $> R_{200}$ from the cluster centre. On the other hand, Maier et al. 2006 has demonstrated, based on a large grid of Pgase2 models, that after the gas inflow is suppressed and eventually stopped, galaxies can increase their gas phase metallicities by a factor of ~ 0.2 dex.

To conclude, the observational results of this thesis show enhanced metallicities for low mass cluster members, as compared to the population of field galaxies at similar redshifts, meaning that strangulation can indeed be considered a plausible mechanism to explain the observed metallicity trends. These findings indicate that the inflow of gas is suppressed and eventually stopped in low mass cluster galaxies, even at radii larger than R_{200} , as a

result of cluster environmental effects, likely due to the removal of the hot halo gas by mild ram-pressure stripping. The cold gas component is, however, not affected, meaning that SF can still occur until there is no more gas left.

A valid explanation to the fact that we observe no substantial difference in the metallicities of accreted and infalling cluster galaxies, is that these systems were probably already affected by ram pressure, as they all reside, in projection, close to the central region of the cluster.

We should also mention that the observed metallicity effects are indeed weak, but this is also due to the fact that we had a low number of objects with middle-resolution observations for the statistics. All cluster members, both infalling and accreted ones, are located close to the cluster core and do not reach the outskirts of the caustic profile, and thus, a meaningful comparison between galaxies of different accretion histories (within/beyond R_{200}) could not be carried out.

Enlarging the sample of RXJ2248 galaxies would allow us to make more accurate statements about the observed metallicity trends, and it would also enable a more meaningful comparison between the different populations.

Appendix A

LePhare of Arnouts and Ilbert et al. 2011

In this section we provide some additional information regarding the mass computation with the LePhare code as well as details to the computation of synthetic Subaru filters.

A.1 Computation of stellar masses

The masses of the cluster members were computed based on their apparent magnitudes in the different WFI bands using the code LePhare of Arnouts and Ilbert et al. 2011. As the U-, Z- and I- bands don't reach magnitudes as low as the B-, V-, R- bands, see figure 3.2, the observed magnitudes in these bands were subsequently left out from the input table for a test computation of the masses. Figure A.1 shows the difference between the stellar masses of the RXJ2248 cluster members as computed when using all the observed magnitudes in the UBVRIZ WFI bands and the stellar masses obtained when using just specific apparent magnitudes, as a function of the stellar masses obtained when using all the observed magnitudes. The scatter is the lowest when excluding the U filter from the input table that is provided to LePhare, and the highest when excluding the I-band. The computation of masses with LePhare is highly dependent on the used apparent magnitude from a specific band, and it is shown to differ depending on which bands are used. To obtain reliable masses, the whole range of observed magnitudes in all the 6 WFI filters were used for the computation.

A.2 Synthetic Subaru BRz observed magnitudes

As the RXJ2248 cluster is the southernmost target of the CLASH-VLT survey, photometry with Subaru is not available. In order to compare the results of this thesis, with the work by Maier

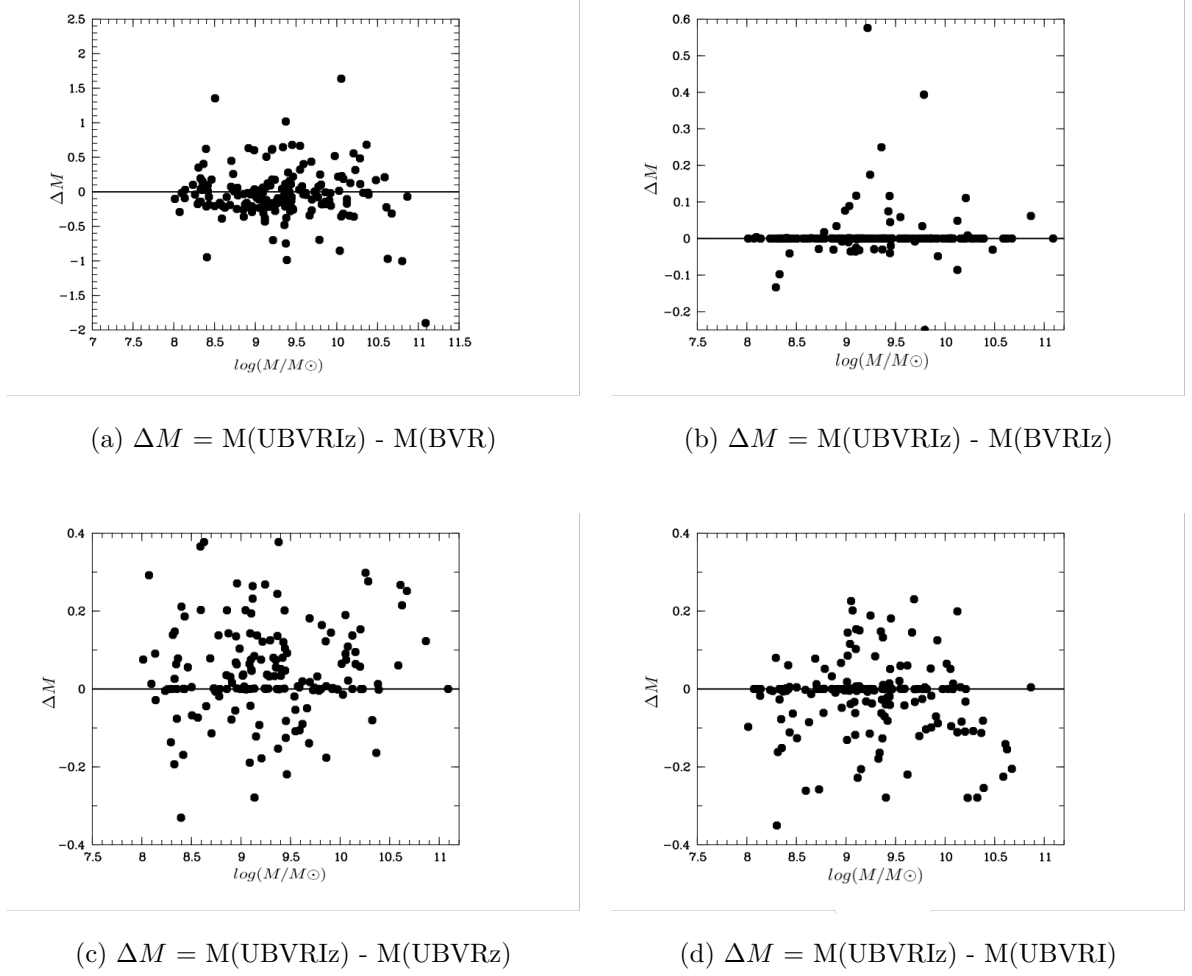


Figure A.1: These plots show the difference between the stellar masses for the cluster members as computed when using all the observed magnitudes in the UBVRIZ WFI bands and the stellar masses obtained when using just specific apparent magnitudes.

et al. 2016, synthetic Subaru BRz absolute magnitudes were computed with LePhare. For this purpose, the input catalog that should be provided to LePhare, containing the UBVRIZ WFI observed magnitudes, should be edited as follows: 6 additional columns for the observed magnitude in Subaru B, R and z-band together with the errors in the respective filters should be included in the table, all filled with the value -99. After these columns, 3 additional ones should be included: CONTEXT, Z-SPEC and STRING where the CONTEXT indicates which passbands can be used for the respective object, Z-SPEC represents the spectroscopic redshift and STRING all the remaining columns in the file which can be left empty. The Context is an integer value which is used to specify the filter combination to be used. This parameter is defined as:

$$\text{Context} = \sum_{i=1}^{i=N} 2^{(i-1)} \quad (\text{A.1})$$

where i stands for the filter number as ordered in the input catalog and in the library, and N is the total number of filters. For example, if an object is observed in all 6 WFI bands - UBVRIZ - and the context for U is 1, the context for B is 2, the one for V is 4, the one for Z is 8, the one for I is 16, and the context for z is 32, then one should fill the column CONTEXT from the input catalog with the value 63 (sum of all context values). If for example an object is observed in all WFI bands, except V, then the CONTEXT column of the input catalog should be filled with the value 59 (subtract from sum of all context values, i.e. 63 the value of the context for the filter V). This input catalog will now have an expanded format given by the parameter **CAT TYPE=LONG**. If one uses a **CAT TYPE=SHORT** version of the catalog, and the CONTEXT is missing, then the code use all the passbands for all the objects. However, LePhare will check the error and flux values and if both values are negative, then that band will not be used. From the configuration file, one needs to edit the filter parameter and extend the list to contain the Subaru filters as well, next to the 6 WFI filters. The rest of the parameters are chosen as described in section 4.2.1. The code will then compute synthetic values for the absolute magnitudes as if the galaxies were observed in the BRz Subaru filters.

The observed magnitudes in the Subaru filters were then computed from the distance modulus:

$$m = M + 5 \log_{10} \left[\frac{D_L}{10 \text{ pc}} \right] + K$$

where m stands for the observed magnitude, M for the absolute magnitude, D_L for the luminosity distance and K for the K-correction. The K-correction is needed for transformations between observed and rest-frame broad-band photometric measurements. This correction accounts for the fact that sources observed at different redshifts are generally compared to standards or to each other at different rest-frame wavelengths. The K-correction thus relates the emitted- or rest-frame absolute magnitude of a source in one photometric bandpass to the observed-frame apparent magnitude of the same source in another bandpass [70]. The values for the K-correction parameter were calculated according to Method 2, described in section 4.2.1.

In order to estimate the errors for the observed synthetic magnitudes in the Subaru filters, the code was ran multiple times by subsequently excluding the observed magnitudes in the WFI I-band, U-band and Z-band from the input table, as these filters don't reach so deep in terms of low brightness. Then, these computed synthetic absolute magnitudes (without the I, U, Z magnitudes), as well as the ones computed when using all of the observed magnitudes in the 6 WFI filters were compared to the median value for the absolute magnitude in each Subaru filter, as estimated from all different runs of the code, and the errors were then calculated. LePhare was run 3 times for each configuration (without the observed magnitude in WFI I-, U-, Z- band and using all the observed magnitudes in WFI UBVRIZ bands.)

Figure A.2 shows the synthetic observed magnitude in the Subaru filters as a function of the errors for the ~ 636 investigated galaxies with available photometric data.

Figure A.3 shows the difference between the colours observed in the WFI B-, R-bands and the Subaru B-, R-bands for the RXJ2248 cluster members. The synthetic Subaru apparent magnitudes are in good agreement to the apparent magnitudes observed in the WFI bands.

Figure A.2: Observed magnitude versus error for the ~ 636 investigated galaxies, for which photometric data is available. The colour code stands for the observed magnitudes in the different synthetic Subaru filters.

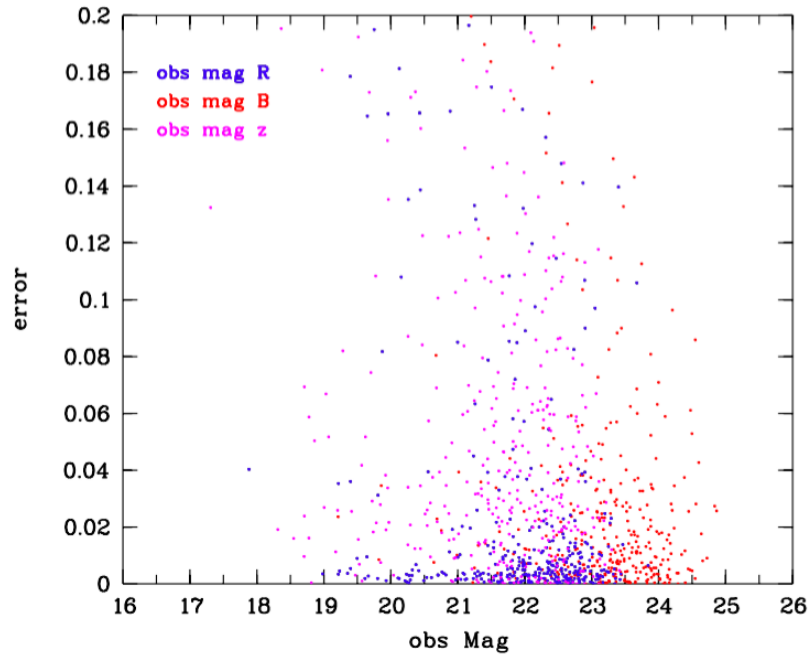
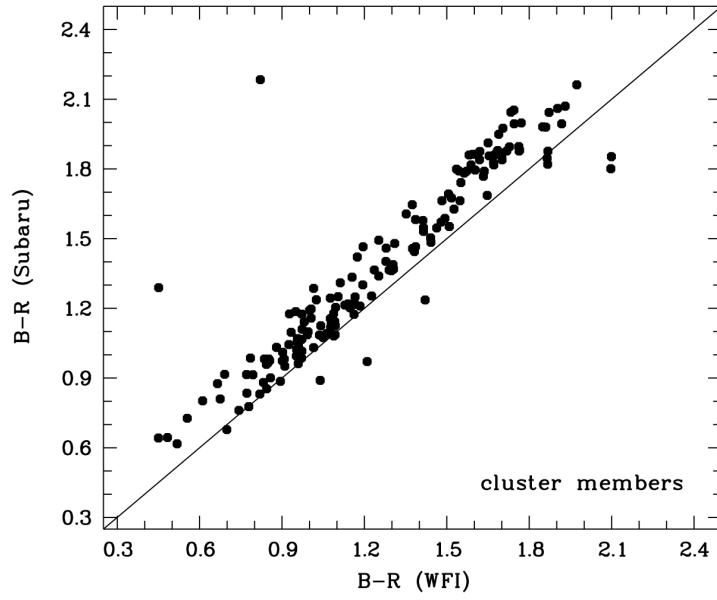


Figure A.3: Observed magnitude in the WFI B, R - band versus the synthetic observed magnitudes in the Subaru B, R - band for the RXJ2248 cluster members.

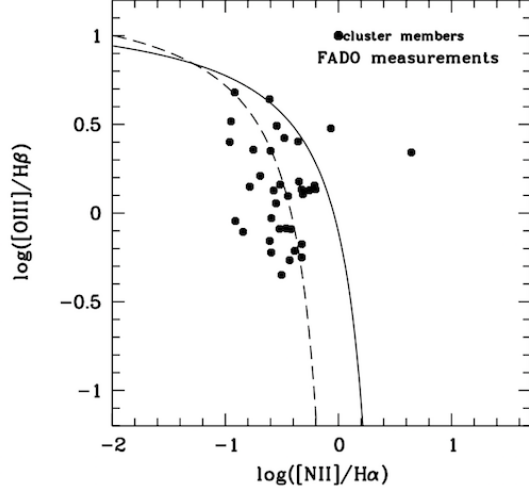


Appendix B

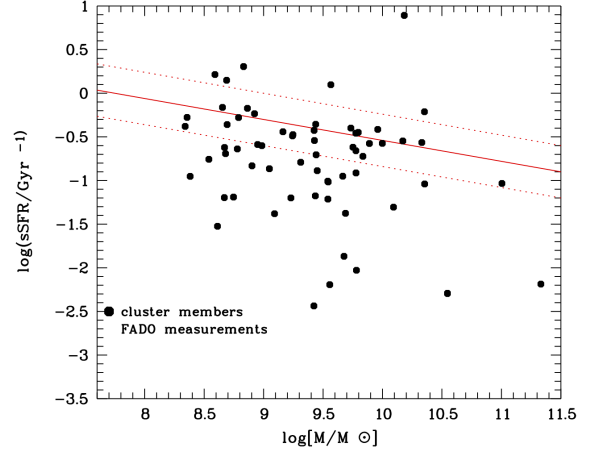
FADO measurements

This chapter contains the main results of this work, namely the AGN contamination of the sample, the sSFR-M and MZR for the RXJ2248 cluster members, as computed when using the flux measurements from FADO. As mentioned earlier, FADO is code specially designed to perform population spectral synthesis in order to derive different physical parameters from a galaxy spectrum, including the emission line fluxes. From the parent sample of 176 RXJ2248 cluster members, FADO measured the fluxes for all 4 emission lines of interest in only 34 galaxy spectra, while when using *splot* in IRAF, we measured all line fluxes in 59 galaxies.

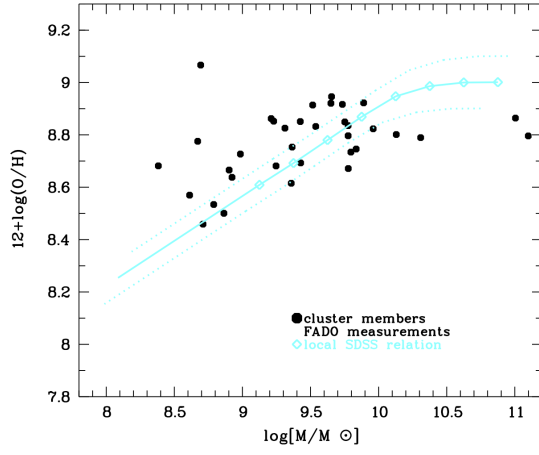
The main results are shown in figure [B.1](#). Panel a. shows the BPT diagnostic diagram for the cluster members. According to this diagnostic diagram, 3 galaxies can be classified as an AGN, as they are located above the two separation curves of Kewley et. al 2002 and Kauffmann et al. 2003b. These 3 galaxies were also classified as AGNs, by both the BPT and WHAN diagnostic diagram, when using the flux measurements from IRAF. Panel b. shows the sSFR-M relation for the RXJ2248 cluster galaxies, as computed when using the luminosity of the $H\alpha$ line. According to this diagram, most galaxies can be classified as SF MS galaxies. However, we also observe a substantial fraction of cluster members, which show lower sSFRs than the MS population, meaning that they form the quenched, passive population. Panels c. and d. show the MZR for the RXJ2248 cluster members. Panel c. plots the oxygen abundance, as derived using the O3N2 calibration of Kewley et. al 2013 on the y axis, vs the stellar masses of the investigated sample of galaxies on the x axis. Panel d. depicts the median offset to the local SDSS MZR for our sample of cluster galaxies. The investigated cluster members seem to follow the local SDSS MZR, showing a ~ 0.2 dex dispersion around this relation. To conclude, the results offered by FADO are in accordance with the results presented in section 5. We have chosen, however, to use the emission line-measurements from *splot* in IRAF, as we managed to measure line-fluxes for more galaxies using the latter method.



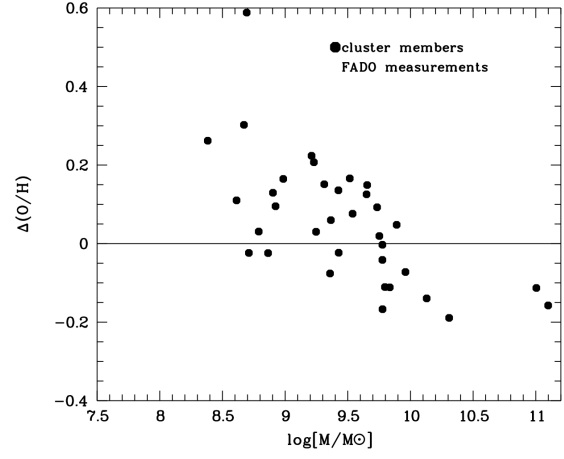
(a) BPT for cluster members.



(b) sSFR-M for cluster members.



(c) MZR for cluster members.



(d) $\Delta(O/H)$ -M for cluster members.

Figure B.1: Main results of this work, using the flux measurements of the emission lines $[OIII]$, $H\beta$, $[NII]$, $H\alpha$ provided by FADO.

Appendix C

MZR

C.1 MZR for RXJ2248 cluster members

This section presents the MZR of the RXJ2248 cluster galaxies, as computed using the 2 metallicity calibrations derived by Maier et al. 2016 for SF galaxies.

Fig. C.1 reproduces the mass-metallicity relation for the RXJ2248 cluster members: the x-axis plots the stellar masses of the cluster members in solar units and the y-axis plots the oxygen abundance as derived through the $[OIII]/H\beta$ calibration of Maier et al. 2016. The panel on the left-hand side shows the MZR for all cluster members which have measurements of the 2 emission lines of interest: $[OIII]$ and $H\beta$. The colour codes stand for the different quality flags assigned to the galaxy spectra. The cyan diamonds and the solid curve represent the local SDSS relation, derived by Tremonti et al. 2004, and the dotted cyan curves represents the 1σ scatter. The metallicity for the SDSS sample was derived using the O3N2 method, however, due to the fact that this calibration also uses the $[OIII]/H\beta$ line ratio, it can still be used as a reference. The black cross in the upper left corner represents the mean error in the (O/H) derivation. The panel on the right-hand side shows the MZR for the 53 cluster members with accurate flux measurements, which were selected for the metallicity study as described in section 4.3.1. The AGNs are also depicted in this plot in red, together with the median (O/H) values for 2 mass bins in green.

Fig. C.2 also displays the mass-metallicity relation for the RXJ2248 cluster members: the x-axis plots the stellar masses of the cluster members in solar units and the y-axis plots the oxygen abundance as computed with the $[NII]/H\alpha$ line ratio method derived by Maier et al. 2016 for main sequence star forming galaxies. The panel on the left-hand side shows the MZR for all RXJ2248 cluster members which have measurements of the 2 emission lines $[NII]$ and $H\alpha$. The oxygen abundances for the SDSS galaxies were derived using the O3N2 method, but as

this calibration also uses the $[NII]/H\alpha$ line ratio, it can be used as a comparison. The panel on the right-hand side reproduces the MZR for the 53 cluster members with accurate line measurements, which were selected for the metallicity study as described in section 4.3.1. All the symbols are the same as in the previous plots. As mentioned in section 5.4.1, this metallicity calibration saturates for high oxygen abundance values, meaning that after a specific threshold, this method does not deliver accurate metallicities any more. As can be seen from this diagram, the $[NII]/H\alpha$ calibration offers the highest values for the oxygen abundance from all the 3 methods used.

An explanation for these high values for the (O/H) can be given by analysing the location of the respective galaxies in the BPT diagnostic diagram. Most galaxies that have $(12+\log(O/H)_{N2}) > 8.8$ are either classified as AGNs (see the 2 red dots) or as composite galaxies, meaning that their ISM is ionised by both a stellar component and an active black hole. Some of these galaxies also fall in the AGN zone of the WHAN diagram. As only high energy photons can excite forbidden lines like $[NII]$, an AGN will have high values for the $[NII]/H\alpha$ line ratio. In this case, a calibration which uses these ELs is not indicated, as the results will be biased. The $[NII]/H\alpha$ metallicity calibration was strictly derived for star forming galaxies and not for AGNs.

Fig. C.3 shows the offset of the MZR of cluster galaxies to the local SDSS MZR, for the (O/H) s computed through the $[OIII]/H\beta$ line ratio method, whereas fig. C.4 plots the difference between the metallicity of local galaxies and the metallicity of the cluster members, as derived through the calibration which uses the $[NII]/H\alpha$ emission line ratio. The plots on the left-hand side show the median offset to the local SDSS MZR for all cluster members which have measurements of the emission lines of interest, while the plots on the right-hand side show the offset to the SDSS MZR as well, but only for cluster members which have a quality flag $f=1$ assigned to their spectra. For a better visualisation, the plots on the left-hand side also shows the median values of the $\Delta(O/H)$ in green. The rest of the symbols are the same as in the previous plots.

C.2 MZR for field galaxies

In this section we present the MZR of field galaxies, as computed using the $[OIII]/H\beta$ metallicity calibration by Maier et al. 2016. Fig. C.5 shows the MZR for the sample of field galaxies from the low redshift bin (left) and from the high redshift bin (right). The gas phase metallicities were derived using the calibration of Maier et al. 2016, based on the flux ratio $[OIII]/H\beta$. The black points in both diagrams stand for the field galaxies, which are described by quality

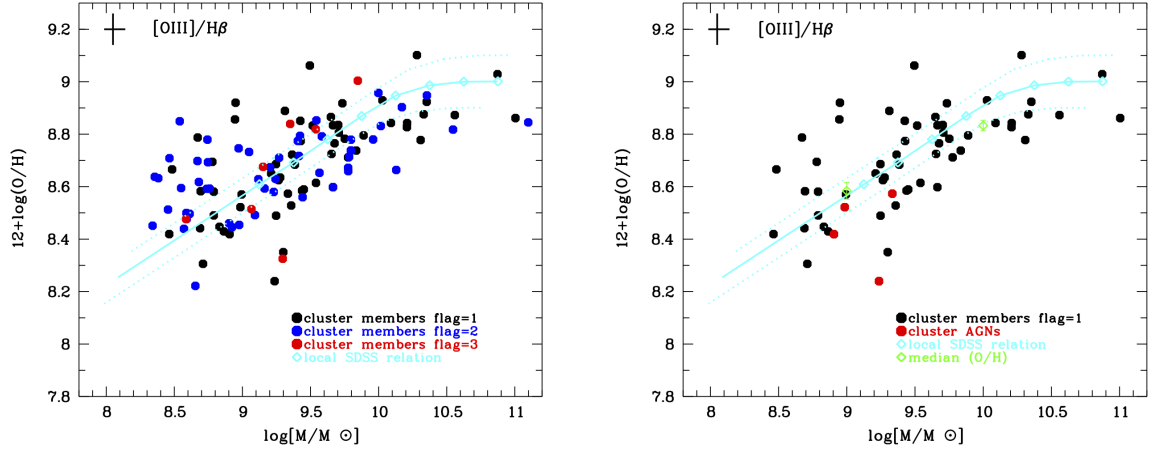


Figure C.1: MZR for RXJ2248 cluster members using the $[OIII]/H\beta$ metallicity calibration derived by Maier et al. 2016 for galaxies in the star-forming main sequence. The panel from the left-hand side shows the MZR for all cluster members, which have flux measurements for the $[OIII]$ and $H\beta$ emission lines. The colour codes black, red and blue stand for the different quality flags assigned to the spectra. The panel on the right-hand side shows the MZR for the cluster members with accurate line measurements, which were selected for the metallicity study. The red points represent the AGNs, as identified by the BPT and WHAN diagnostic diagrams, while the green open diamonds show the median value of the (O/H) s. The cyan diamonds and curves from both panels show the local SDSS relation with the 1σ scatter. The black cross in the upper left corner represents the mean error of the (O/H) derivation.

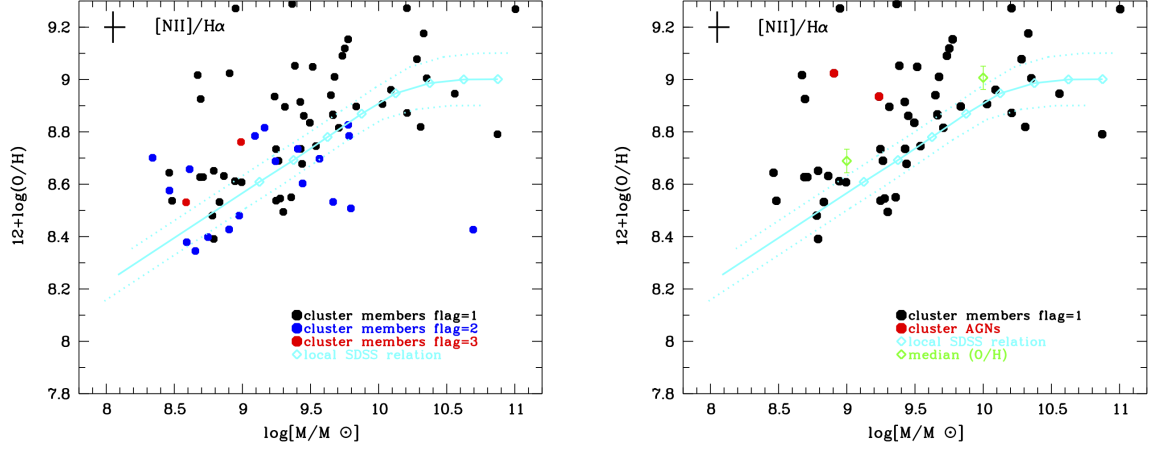


Figure C.2: MZR for RXJ2248 cluster members using the $[NII]/H\alpha$ line ratio metallicity calibration derived by Maier et al. 2016 for galaxies which follow the star-forming main sequence. The panel from the left-hand side shows the MZR for all cluster members which have flux measurements of the $[NII]$ and $H\alpha$ emission lines. The colour codes black, red and blue stand for the different quality flags describing the spectra of these galaxies. The panel from the left-hand side shows the MZR only for the cluster members described by a quality flag $f=1$, which were chosen for the metallicity study. The red points represent the AGNs, as identified by the BPT and WHAN diagnostic diagrams. The green diamonds show the median values of the (O/H) s. The cyan diamonds and curves from both panels represent the local SDSS relation with the 1σ scatter. In both panels, the black cross represents the mean error of the (O/H) derivation.

Values of $(12 + \log(O/H)_{N2}) > 9$ should not be taken into account as this method is known to saturate at high values for the metallicity. The galaxies which show such increased metallicities fall in the composite zone of the BPT diagnostic diagram, meaning that they have high values for the $[NII]/H\alpha$ line ratio, and thus, this calibration is not applicable for these cases.

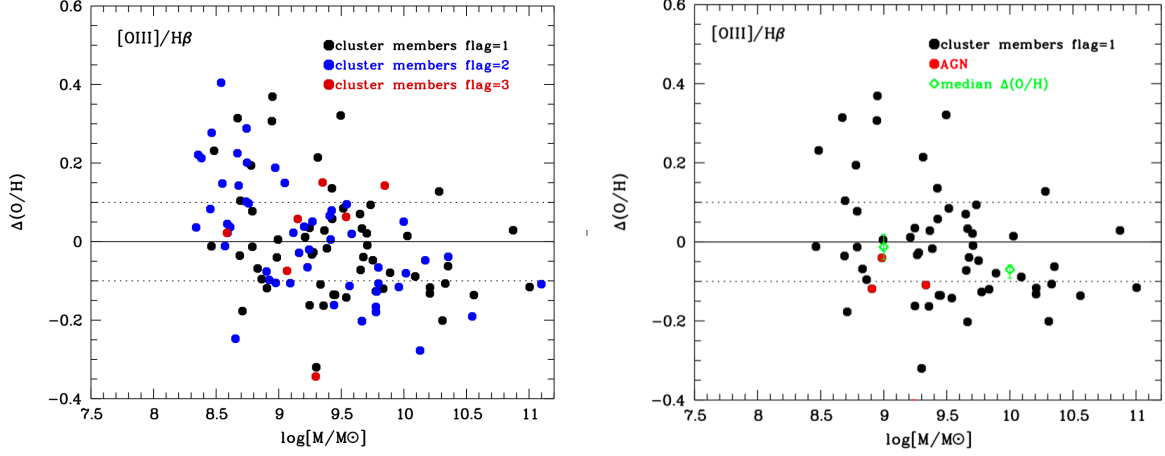


Figure C.3: The median offset to the local SDSS MZR for the RXJ2248 cluster members, whose (O/H) s were calculated through the calibration based on the $[OIII]/H\beta$ line ratio. The plot on the left-hand side shows the offset to the local MZR for all cluster members with available flux measurements, while the panel from the right-hand side shows the same, but only for the members which have a quality flag $f=1$ assigned to their spectra. For a better visualisation, the median values of the offset to the local SDSS MZR are shown as green open diamonds.

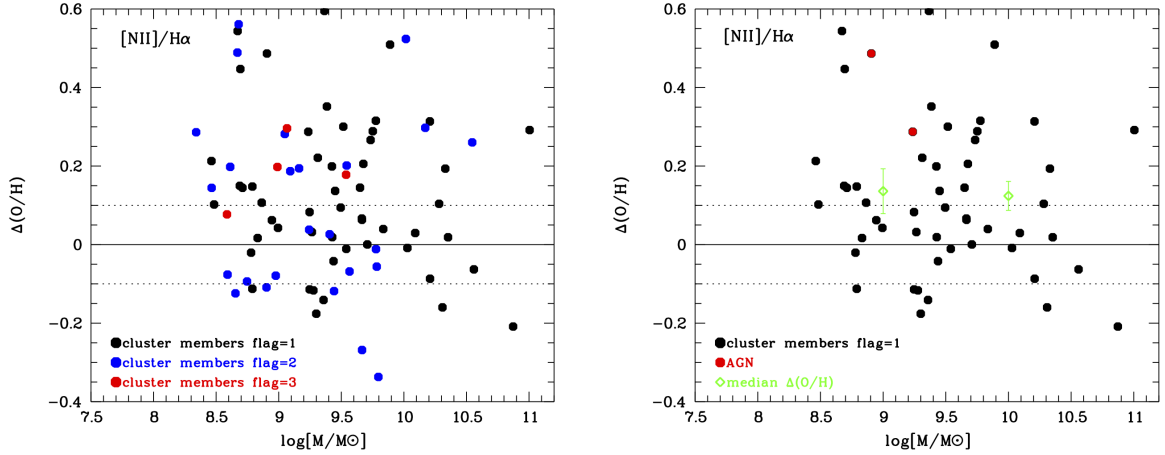


Figure C.4: The median offset to the local SDSS MZR for the RXJ2248 cluster members, whose (O/H) s were calculated through the $[NII]/H\alpha$ emission line ratio calibration. The plot on the left-hand side shows the offset to the local MZR for all cluster members with available flux measurements, while the panel from the right-hand side shows the same, but only for the members which have a quality flag $f=1$ assigned to their spectra. The median values of the offset to the local SDSS MZR are shown as green open diamonds

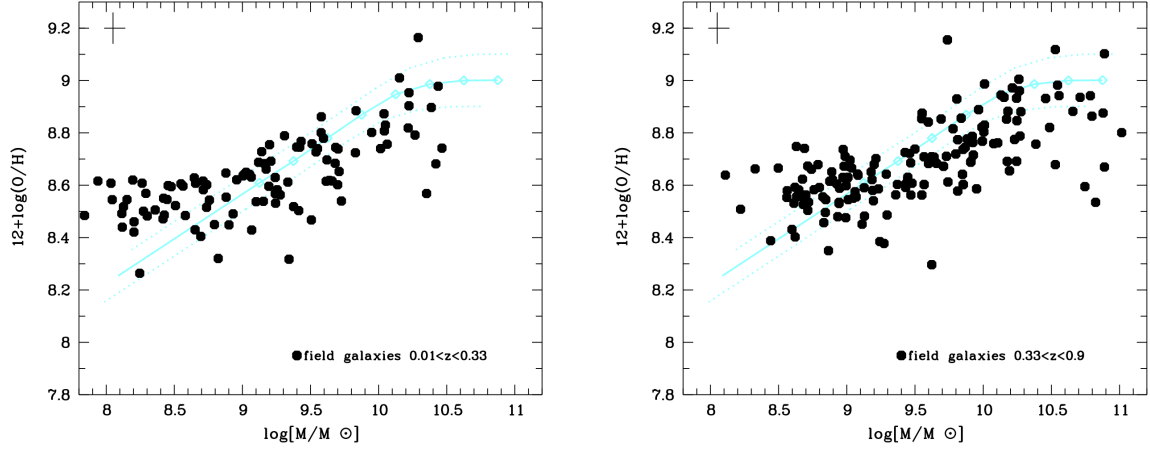


Figure C.5: MZR for field galaxies using the metallicity calibration of Maier et al. 2016, based on the emission line ratio $[OIII]/H\beta$. The diagram from the left-hand side shows the MZR for the field galaxies from the low redshift bin, while the plot from the right-hand side shows the MZR for the field galaxies from the high redshift bin. The black, filled dots represent the field galaxies, which are described by a quality flag $f=1$, having available measurements of the $[OIII]$, $H\beta$ line fluxes. The cyan diamonds and curves represent the local SDSS relation with its 1σ scatter.

flags $f=1$. The cyan diamonds and solid curve represent the local SDSS MZR, while the cyan dotted lines stand for the 1σ dispersion of this relation. The cross from the upper left corner in both diagrams shows the median error in the (O/H) derivation. Fig. C.6 shows the difference between the measured (O/H) s of field galaxies from the low redshift bin $0.01 < z < 0.33$ (left) and high redshift bin $0.36 < z < 0.9$ (right), using the $[OIII]/H\beta$ calibration, and the (O/H) s of local SDSS galaxies, as a function of the stellar masses. The black dots stand for the field galaxies with accurate line measurements.

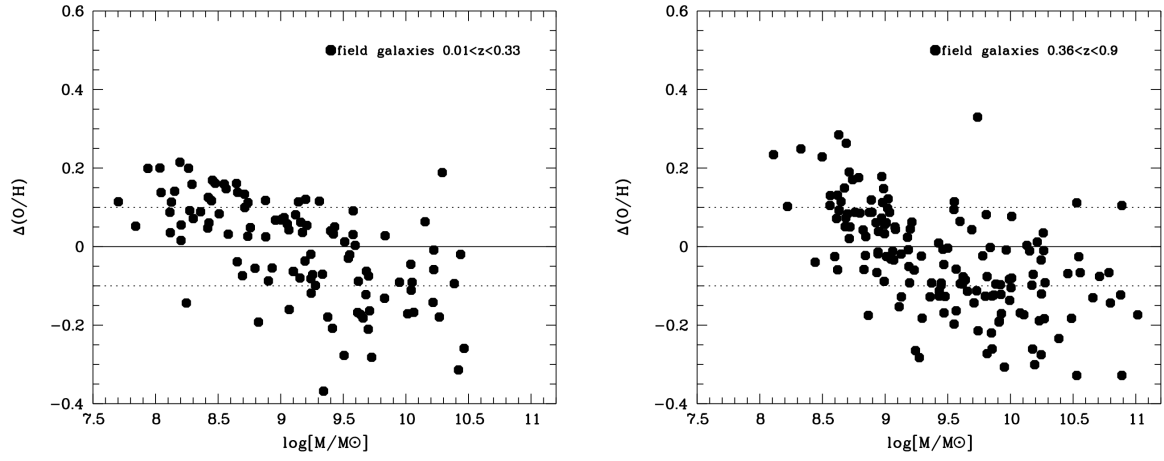


Figure C.6: The median offset of the (O/H)s of field galaxies from the low (left) and high (right) redshift bin, whose (O/H)s were calculated through the $[OIII]/H\beta$ calibration, to the MZR of local SDSS galaxies.

Appendix D

Phase Space

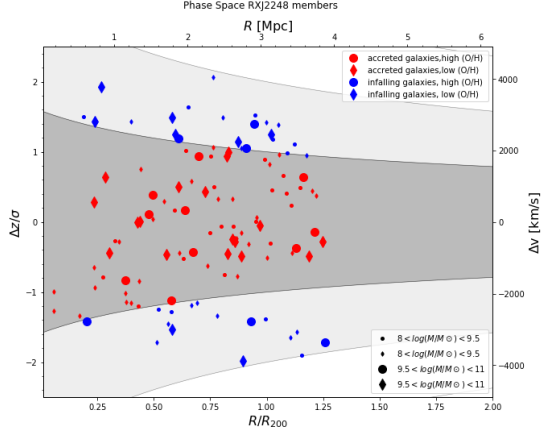
In this section, we investigate the distribution of the cluster galaxies in projected phase space, according to their gas-phase metallicities.

Figure D.1 also shows the distribution of cluster galaxies in projected phase space, with the symbols denoting the different gas-phase metallicities and masses of the galaxies. The small symbols represent the sample of galaxies from the low mass bin $8 < \log(M/M_\odot) < 9.5$ and the large symbols the galaxies from the high mass bin $9.5 < \log(M/M_\odot) < 11$. For the plot on the left-hand side, the (O/H)s were computed through the O3N2 method, whereas for the panel on the right-hand side, the metallicities were derived using the $[OIII]/H\beta$ calibration. The red symbols represent the population of accreted cluster members. The small circles show the galaxies, which have gas-phase metallicities higher than the median (O/H) value for the low mass bin ($(O/H)_{median,O3N2} = 8.6714$ -left; $(O/H)_{median,[OIII]/H\beta} = 8.6212$ -right), while the small diamonds represent the sample of galaxies with higher (O/H)s than this threshold. The large circles stand for the galaxies with gas phase metallicities higher than the median (O/H) value for the high mass bin ($(O/H)_{median,O3N2} = 8.8851$ -left; $(O/H)_{median,[OIII]/H\beta} = 8.8059$ -right), while the large diamonds represent the galaxies with metallicities lower than this value. The blue symbols stand for the recently accreted cluster galaxies. The small circles show the galaxies, which have gas-phase metallicities higher than the median (O/H) value for the low mass, infalling galaxies ($(O/H)_{median,O3N2} = 8.6861$ -left; $(O/H)_{[OIII]/H\beta} = 8.6502$ -right), while the small diamonds represent the sample of galaxies with higher (O/H)s than this threshold. The large circles stand for the galaxies with gas phase metallicities higher than the median (O/H) value for the high mass bin ($(O/H)_{median,O3N} = 8.8837$ -left; $(O/H)_{[OIII]/H\beta} = 8.8426$ -right), while the large diamonds represent the galaxies with (O/H)s lower than this value. According to this diagram, gas-phase metallicities of cluster members seem to be randomly distributed throughout the phase-space, with no particular trend observable. Both high and low Z galaxies

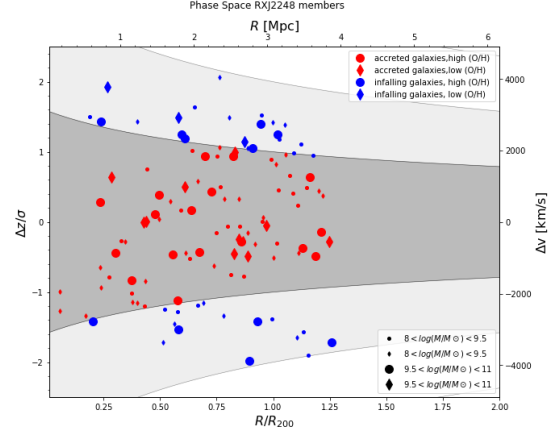
populate all regions of this diagram.

Fig D.2 shows the phase-space diagram for all the RXJ2248 cluster members, colour-coded according to their (O/H), as derived using the O3N2 calibration of Kewley et. al 2013 (left-hand side) and the $[OIII]/H\beta$ calibration of Maier et. al 2016 (right-hand side). The blue squares represent the galaxies with low metallicities (below the local SDSS MZR: $\Delta(O/H) < -0.15$), the green diamonds stand for the galaxies with enhanced metallicities (above local SDSS MZR: $\Delta(O/H) > 0.15$), the red stars denote the galaxies which have gas-phase metallicities consistent to the local SDSS MZR ($-0.15 < \Delta(O/H) < 0.15$), and the black points show the galaxies with no (O/H) measurements. All cluster galaxies are considered, regardless of the quality flag assigned to their spectra.

Based on fig. D.2, one can notice that at distances from the cluster centre lower than R_{500} , all cluster members show gas-phase metallicities which are consistent to the local SDSS MZR. When analysing the panel from the left-hand side of fig D.2, where (O/H)s were calculated using the O3N2 method, we get the following: 4.9% of cluster members have (O/H)s lower than the local MZR, 22.95 % have gas metallicities higher than the MZR and 72.13 % show metallicities consistent to the local MZR (only $f=1$ galaxies, and no composite galaxies considered). While the population which has (O/H)s consistent to the local MZR is more or less uniformly distributed throughout the cluster, both in the virialized population region and in the infalling region, one observes a tendency of high-metallicity galaxies to accumulate within the 1σ contour of the caustic. We can also notice that the galaxies with low gas-phase metallicities seem to increase in numbers with larger distances from the clusters centre, i.e. beyond R_{500} and also beyond the 1σ contour of the caustic. The same can be seen in the right panel of fig. D.2, where (O/H)s were calculated using the $[OIII]/H\beta$ line ratio method. In this case, we get 10.9% of cluster galaxies with lower metallicities than the local relation, 17.18% with higher (O/H)s and 71,8 % with gas-phase metallicities consistent to the local MZR (only $f=1$ galaxies, and no composite galaxies considered). Again, we can notice an increase in the fraction of galaxies with lower metallicities towards the outer region of the cluster. Regarding the galaxies with (O/H)s above the local MZR, they seem to concentrate in the region populated by the accreted and possibly virialised galaxies.

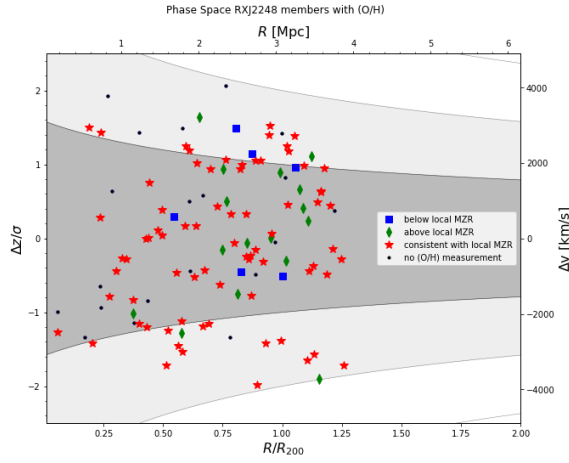


(a) O3N2, all galaxies

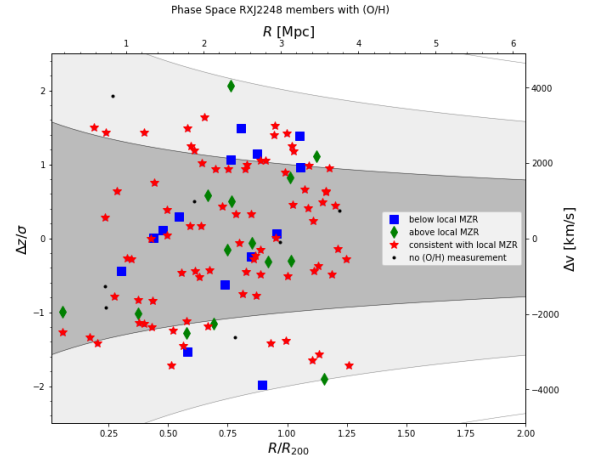


(b) $[OIII]/H\beta$, all galaxies

Figure D.1: Cluster centric radius vs. line-of-sight velocity for the RXJ2248 cluster members. The red symbols located within 1σ (dark-grey shaded area) are considered to be virialised cluster members, which are in dynamical equilibrium with the clusters' potential. The blue symbols which are located between $2\sigma - 3\sigma$ (light grey shaded area) are classified as infalling galaxies, which have been recently accreted into the cluster. The size of the symbols stand for the 2 different mass bins: the small symbols represent the galaxies with $8 < \log(M/M_{\odot}) < 9.5$, where as the large symbols stand for the galaxies with $9.5 < \log(M/M_{\odot}) < 11$. The circles represent the sample of galaxies with enhanced metallicities, while the diamonds represent the galaxies with lower (O/H) values. Gas phase metallicities were computed through the O3N2 method (left) and $[OIII]/H\beta$ calibration (right). More details are given in the text.



(a) O3N2, all galaxies



(b) $[OIII]/H\beta$, all galaxies

Figure D.2: Cluster centric radius vs. line-of-sight velocity for the RXJ2248 cluster members. The symbols located within 1σ (dark-grey shaded area) are considered to be virialised cluster members, which are in dynamical equilibrium with the clusters' potential. The symbols which are located between $2\sigma - 3\sigma$ (light grey shaded area) are classified as infalling galaxies, which have been recently accreted into the cluster. The colour codes are the same as in the previous plots. The (O/H)s for the galaxies shown on the left-hand side were computed using the O3N2 calibration of Kewley et. al 2013, while the ones for the galaxies displayed in the right-hand panel were derived using the $[OIII]/H\beta$ calibration of Maier and Ziegler et al. 2016.

Appendix E

(O/H) comparison between field galaxies and cluster members at different cluster centric radii

In this section we perform the same analysis as in section 5.8.1, but by using the (O/H)s computed through the $[OIII]/H\beta$ calibration by Maier et al. 2016. Fig. E.1 shows the MZR of field galaxies and accreted cluster members on the left-hand side and the MZR of field galaxies and infalling cluster galaxies on the right-hand side. The accretion histories of the cluster members are defined according to the phase-space analysis: galaxies residing within 1σ represent the accreted cluster members, while galaxies which reside between $1\sigma - 2\sigma$ represent the infalling cluster members. The black symbols in both plots stand for the cluster galaxies, the blue ones for the field population with $0.3 < z < 0.4$, while the cyan diamonds and curves represent the local SDSS MZR. The black and blue diamonds represent the median (O/H) values of cluster and field galaxies respectively. Both galaxies described by a quality flag $f=1$ and $f=2$ are considered. The oxygen abundances were computed using the $[OIII]/H\beta$ calibration by Maier et al. 2016. For a better visualisation, fig. E.2 shows the (O/H) distribution (O3N2 calibration) of field galaxies with $0.3 < z < 0.4$ and cluster members with different accretion histories. The plots from the upper 2 panels show the distribution of the (O/H)s of accreted cluster members (black histogram) as compared to the (O/H) distribution of field galaxies (blue histogram) from the low M bin (left) and high M bin (right). The dashed black line represents the median (O/H) value for accreted cluster members in the respective mass bin, while the blue dashed line stands for the median (O/H) value for field galaxies. The lower 2 panels display the (O/H) distribution of accreted cluster members (black histograms) as compared to the (O/H) distribution of infalling cluster members (blue histograms) from the low M bin (left) and high M bin (right). The

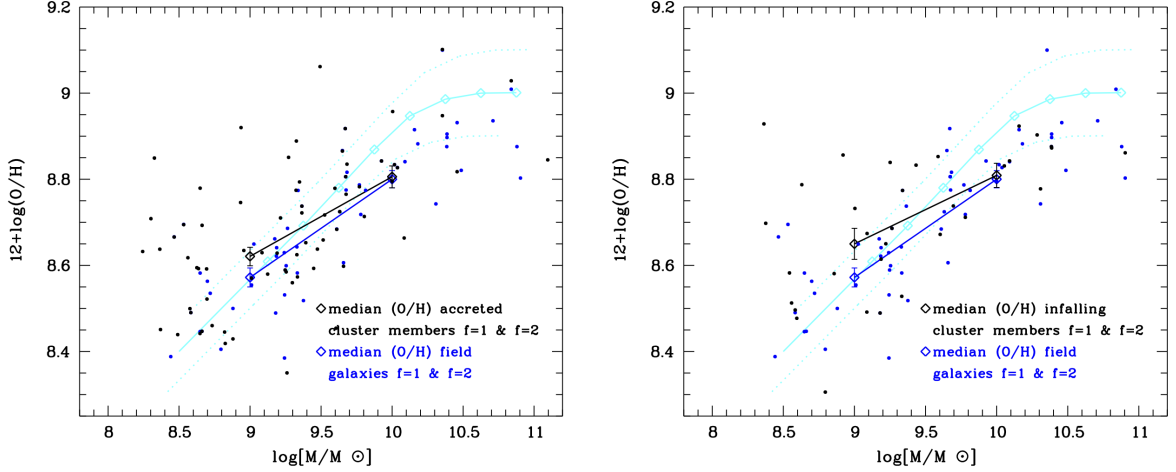


Figure E.1: MZR for cluster members with different accretion histories and field galaxies with $0.3 < z < 0.4$ using the $[OIII]/H\beta$ calibration of Maier et. al 2016. The plot on the left-hand side depicts the MZR for field galaxies (blue dots) as compared to the MZR of accreted RXJ2248 cluster members (black dots). The plot on the right-hand side shows the (O/H) comparison between field galaxies and infalling cluster members. For a meaningful comparison, the sample of galaxies was divided into 2 mass bins: $8.3 < \log(M/M\odot) < 9.5$ and $9.5 < \log(M/M\odot) < 11$. The median (O/H)s of field and cluster galaxies in each mass bin were compared to each other: the black diamonds stand for the median (O/H) of cluster members with different accretion histories, while the blue ones represent the median (O/H) of field galaxies. The cyan diamonds and curves stand for the local SDSS MZR.

dashed black line stands for the median (O/H) value for accreted cluster galaxies and the blue one for the median (O/H) of infalling cluster galaxies. Fig. E.3 and E.4 show the same, but in this case, the distinction between infalling and accreted cluster galaxies was done by imposing the R_{500} criterion: accreted cluster galaxies are defined as lying between the 1σ contour of the caustic and at distances from the cluster centre $R < R_{500}$, while infalling galaxies were classified as lying both between 1σ contour, but at distances from the cluster centre $R > R_{500}$, and between the 1σ - 2σ contour of the caustic profile. For both cases, the same trends as earlier can be observed: both accreted and infalling cluster galaxies from the low mass end show more enhanced metallicities than field galaxies, while at the high mass end, metallicities of both field and cluster galaxies are comparable. On the other hand, accreted and infalling galaxies show similar (O/H)s.

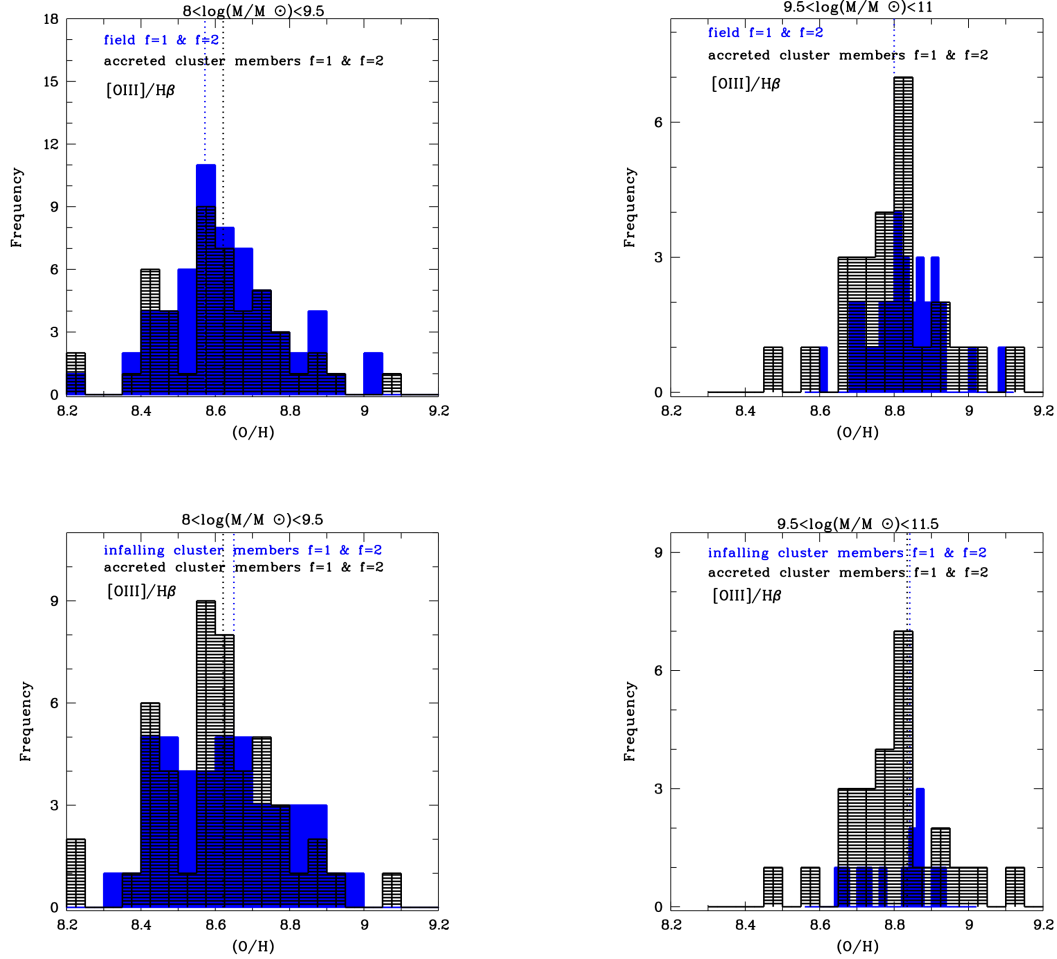


Figure E.2: (O/H) distribution ($[OIII]/H\beta$) for field galaxies, accreted and infalling cluster members, divided into 2 mass bins. The plots from the upper 2 panels show the distribution of the gas phase metallicities for accreted cluster members (black histogram) as compared to the (O/H) distribution of field galaxies (blue histogram). The graphs from the lower 2 panels show the (O/H) distribution of accreted cluster members (black histograms) as compared to the (O/H) distribution of infalling cluster members (blue histograms). The dashed lines in all plots stand for the median (O/H) value of the respective sample of galaxies, colour coded accordingly.

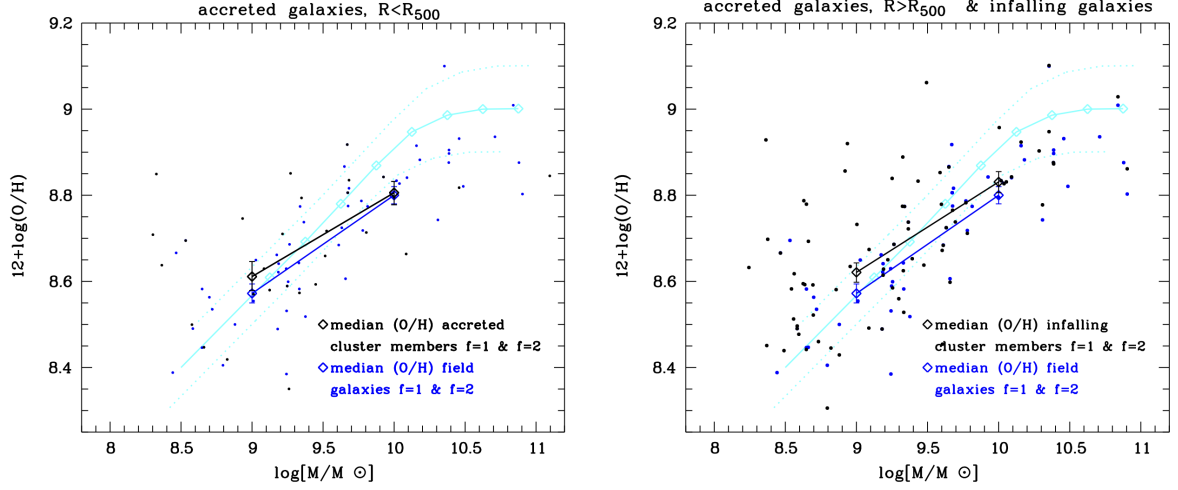


Figure E.3: MZR for cluster members with different accretion histories and field galaxies with $0.3 < z < 0.4$ using the $[\text{OIII}]/\text{H}\beta$ calibration of Maier et. al 2016. The plot on the left-hand side depicts the MZR for field galaxies (blue dots) as compared to the MZR of accreted (**within** 1σ **and** $R < R_{500}$) RXJ2248 cluster members (black dots). The plot on the right-hand side shows the (O/H) comparison between field galaxies and infalling cluster members (**within** 1σ **and** $R > R_{500}$ **and between** $1\sigma - 2\sigma$). For a meaningful comparison, the sample of galaxies was divided into 2 mass bins: $8.3 < \log(M/M\odot) < 9.5$ and $9.5 < \log(M/M\odot) < 11$. The median (O/H)s of field and cluster galaxies in each mass bin were compared to each other: the black diamonds stand for the median (O/H) of cluster members with different accretion histories, while the blue ones represent the median (O/H) of field galaxies. The cyan diamonds and curves stand for the local SDSS MZR.

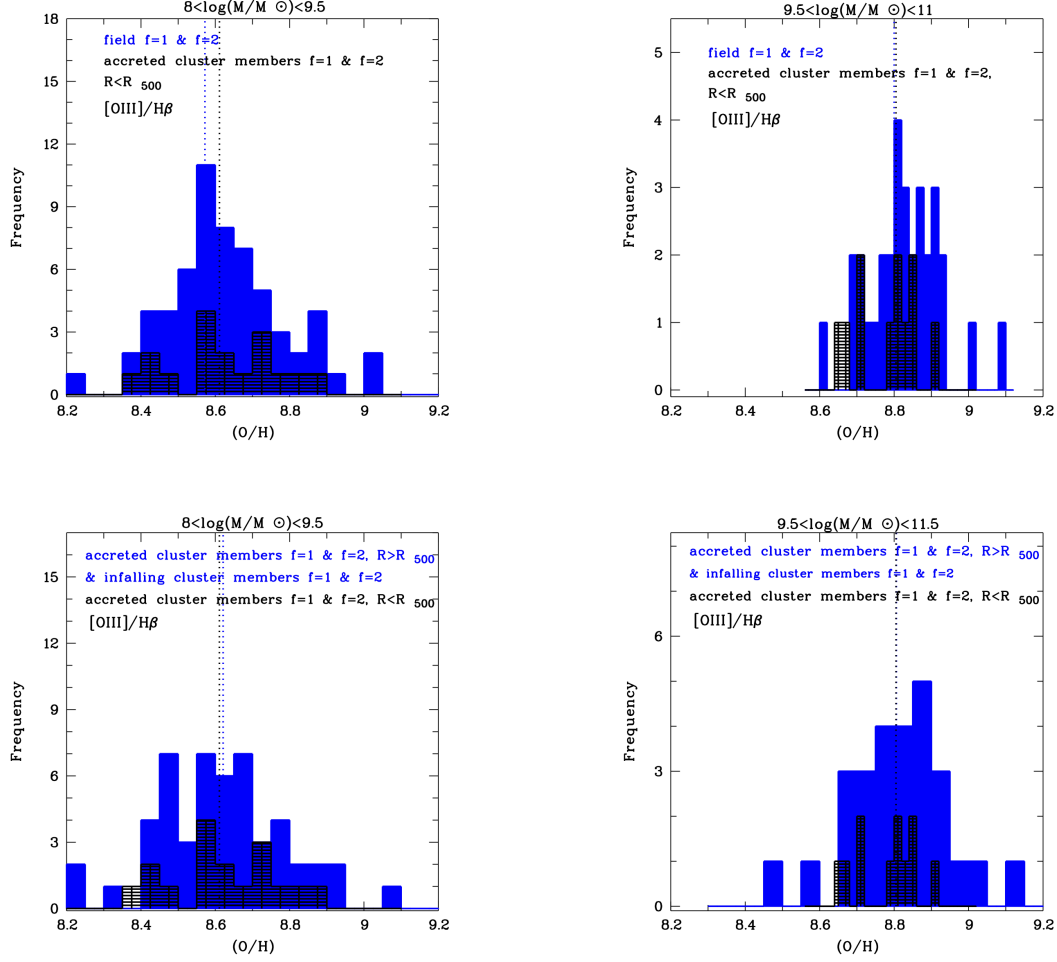


Figure E.4: (O/H) distribution ($[OIII]/H\beta$) for field galaxies, accreted and infalling cluster members (according to the new classification), divided into 2 mass bins. The plots from the upper 2 panels show the distribution of the gas phase metallicities for accreted cluster members (black histogram) as compared to the (O/H) distribution of field galaxies (blue histogram). The graphs from the lower 2 panels show the (O/H) distribution of accreted cluster members (black histograms) as compared to the (O/H) distribution of infalling cluster members (blue histograms). The dashed lines in all plots stand for the median (O/H) of the respective sample of galaxies, colour coded accordingly.

Appendix F

The fundamental metallicity relation

F.1 The fundamental metallicity relation $Z(M, \text{SFR})$ for the RXJ2248 galaxies

In this section, we present the FMR of cluster galaxies, as derived using the 2 metallicity calibrations based on the $[OIII]/H\beta$ and $[NII]/H\alpha$ EL ratios. Fig. F.1 and fig. F.2 show the difference between the measured (O/H)s for the RXJ2248 cluster galaxies and the expected (O/H) values from the FMR expectation of Lilly et al. 2013 (equation 5.56), for the two different scenarios: a metal enriched gas inflow $Z_0/y = 0.1$ (filled circles) and a primordial gas inflow $Z_0/y = 0$ (open circles). Fig. F.1 shows the difference between the (O/H)s computed through the metallicity calibration which uses the $[OIII]/H\beta$ line ratio and the expected values from the model, whereas fig. F.2 shows the difference between the (O/H)s derived through the $[NII]/H\alpha$ calibration and the expected values from the gas regulated model. In both diagrams, the plots on the left-hand side show the difference between measured and predicted metallicities for all RXJ2248 cluster members, which have flux measurements of the emission lines used by the respective metallicity calibration, while the plots on the right-hand side show the same, but only for galaxies described by a quality flag $f=1$.

Based on these diagrams, one can conclude the following: high mass cluster galaxies seem to be in accordance to the model predictions, assuming both metal rich and primordial gas inflow, while low mass galaxies deviate systematically from the predicted (O/H) values of the gas-regulated model, being more in accordance with models which assume a metal rich gas inflow.

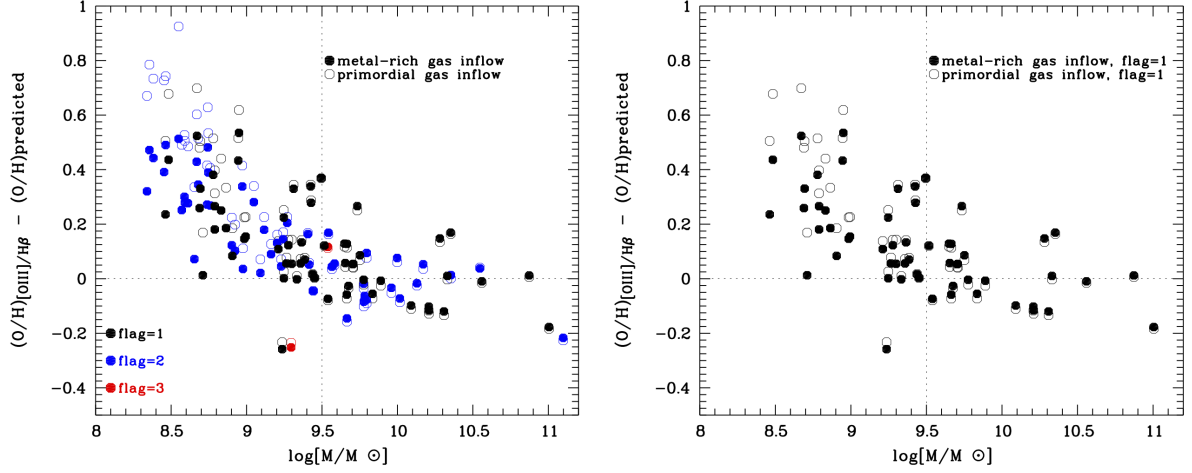


Figure F.1: Difference between the derived (O/H) s for the RXJ2249 cluster galaxies, using the $[OIII]/H\beta$ metallicity calibration, and the expected (O/H) s from the formulations of Lilly et al. 2013 for different infall metallicities Z_0 relative to the yield y , $Z_0/y = 0.1$ (metal enriched gas inflow, filled circles) and $Z_0/y = 0$ (primordial gas inflow, open circles). The panel on the left-hand side shows the difference between the measured and predicted oxygen abundances for the whole sample of RXJ2248 cluster members with available measurements of the emission lines $[OIII]$ and $H\beta$. The colours stand for the different quality flags assigned to the spectra. The panel on the right-hand side also shows the difference between measured and predicted (O/H) s, but only for the cluster members described by a quality flag $f=1$.

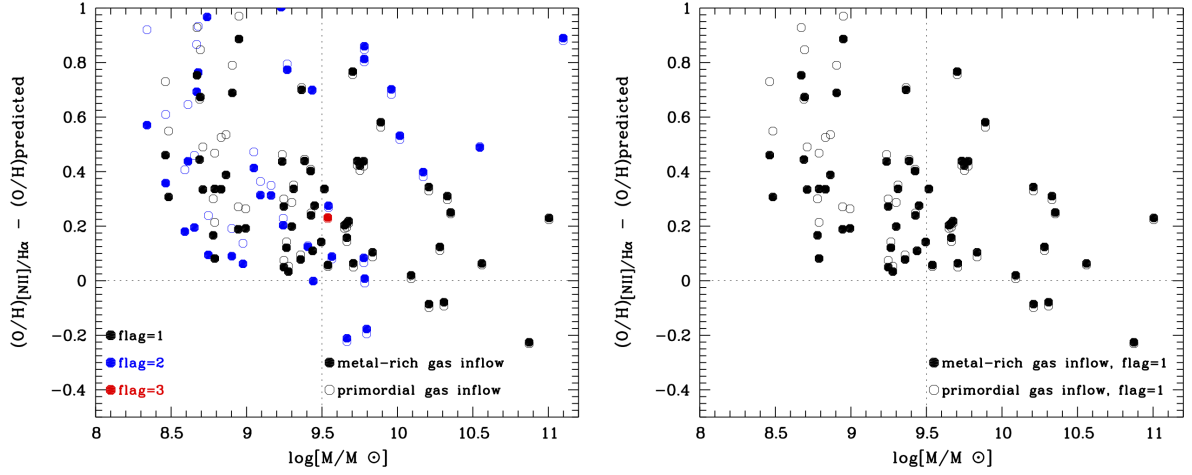


Figure F.2: Difference between the (O/H) s for the RXJ2249 cluster galaxies, computed with the $[NII]/H\alpha$ metallicity calibration, and the expected (O/H) s from the formulations of Lilly et al. 2013 for different infall metallicities Z_0 relative to the yield y , $Z_0/y = 0.1$ (metal enriched gas inflow, filled circles) and $Z_0/y = 0$ (primordial gas inflow, open circles). The panel on the left-hand side shows the difference between the measured and predicted oxygen abundances for the whole sample of RXJ2248 cluster members with available measurements of the emission lines $[NII]$ and $H\alpha$. The different colours stand for the different quality flags assigned to the spectra. The panel on the right-hand side also shows the difference between measured and predicted (O/H) s, but only for the cluster members described by a quality flag $f=1$.

F.2 The fundamental metallicity relation $Z(M, \text{SFR})$ for the field galaxies

Fig. F.3 shows the difference between the measured (O/H)s for the comparison sample of field galaxies with $0.3 < z < 0.4$, using the metallicity calibration based on the $[OIII]/H\beta$ line ratio and the expected (O/H)s from the formulations of Lilly et al. 2013 for different infall metallicities Z_0 relative to the yield y , $Z_0/y = 0.1$ (metal enriched gas inflow, filled circles) and $Z_0/y = 0$ (primordial gas inflow, open circles). All field galaxies described by a quality flag $f=1$ are considered.

Fig. F.4 and F.5 show the difference between the measured (O/H)s for the whole sample of field galaxies and the expected (O/H) values from the FMR expectation of Lilly et al. 2013 (equation 5.56) for two different scenarios: a metal enriched gas inflow $Z_0/y = 0.1$ (filled circles) and a primordial gas inflow $Z_0/y = 0$ (open circles). Figure F.4 shows the difference between (O/H)s measured using the O3N2 metallicity calibration of Kewley et al. 2013 and the predicted values from the formulation of Lilly et al. 2013, for field galaxies in the low redshift bin $0.01 < z < 0.33$ (left) and high redshift bin $0.36 < z < 0.9$ (right). Fig. F.5 shows the same, but in this case, gas phase metallicities were computed using the $[OIII]/[H\beta]$ calibration of Maier et al. 2016. In all of the plots, the black points represent the field galaxies with accurate measurements of the emission lines of interest, whose spectra are described by a quality flag $f=1$.

At all redshifts, high mass field galaxies seem to have oxygen abundances in accordance with the predictions of the FMR, for both a metal-rich and primordial gas inflow. At the low mass end, however, this does not seem to be the case any more. For both the high and low redshift bin, the less massive galaxies seem to have higher gas metallicities than predicted. These galaxies are also more in accordance with the models which assume an inflow of metal enriched gas, than with the models which assume a pristine gas inflow.

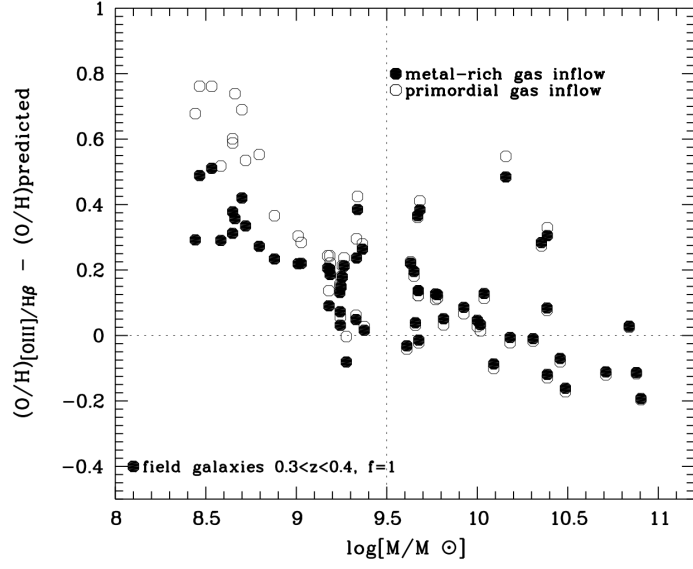


Figure F.3: Difference between the measured (O/H)s for the comparison sample of field galaxies with $0.3 < z < 0.4$, using the $[OIII]/H\beta$ metallicity calibration and the expected (O/H)s from the formulations of Lilly et al. 2013 for different infall metallicities Z_0 relative to the yield y , $Z_0/y = 0.1$ (metal enriched gas inflow, filled circles) and $Z_0/y = 0$ (primordial gas inflow, open circles).

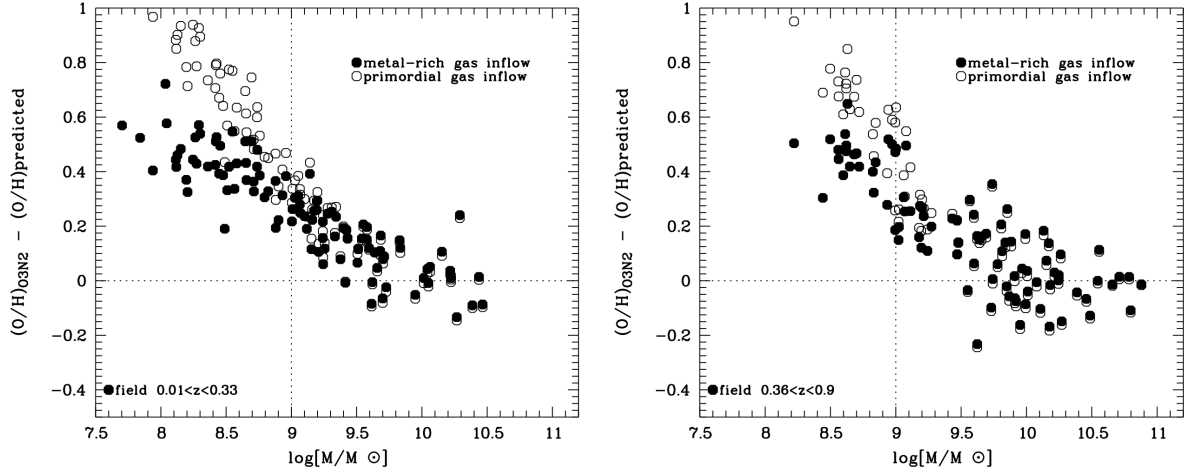


Figure F.4: Difference between the measured (O/H) s for low-redshift (left) and high-redshift (right) field galaxies, using the O3N2 metallicity calibration, and the expected (O/H) s from the formulations of Lilly et al. 2013 for different infall metallicities Z_0 relative to the yield y , $Z_0/y = 0.1$ (metal enriched gas inflow, filled circles) and $Z_0/y = 0$ (primordial gas inflow, open circles).

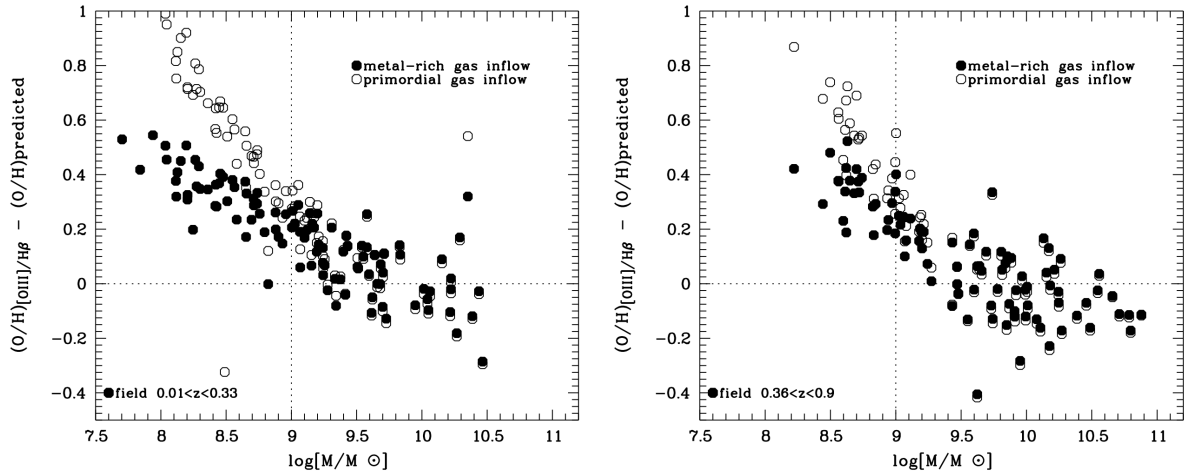


Figure F.5: Difference between the measured (O/H) s for low-redshift (left) and high-redshift (right) field galaxies, using the metallicity calibration based on the $[OIII]/H\beta$ line ratio, and the expected (O/H) s from the formulations of Lilly et al. 2013 for different infall metallicities Z_0 relative to the yield y , $Z_0/y = 0.1$ (metal enriched gas inflow, filled circles) and $Z_0/y = 0$ (primordial gas inflow, open circles).

Appendix G

Tables

Table G1 shows the RXJ2248 cluster galaxies with their respective redshifts, the fluxes of the emission lines $H\beta$, [OIII], $H\alpha$, [NII] in units $10^{-17} \text{erg/s/cm}^2/\text{\AA}$ together with the errors of the flux measurements, the equivalent width of the $H\beta$ and $H\alpha$ ELs, the quality flag assigned to the spectrum, describing the success of the line measurements, the stellar mass, as computed by LePhare, the oxygen abundance derived through the O3N2 method and the SFR in units $M_{\odot}/\text{Gyr}^{-1}$, as computed using the luminosity of the $H\alpha$ EL.

Table G.1: Catalog for the RXJ2248 cluster galaxies.

Galaxy ID	z	$F(H\beta)$	$F([OIII])$	$F(H\alpha)$	$F([NII])$	$EW_{H\beta}$	$EW_{H\alpha}$	f	$\log(M \text{ } M_{\odot})$	$12 + \log(O/H)$	SFR/Gyr^{-1}
40941	0.3570	1.13 $\pm$ 0.12	2.77 $\pm$ 0.18	4.03 $\pm$ 0.15	1.28 $\pm$ 0.30	-22.19	-57.69	1	8.69340e+00	8.70362e+00	2.12268e-01
40209	0.3420	* $\pm$ *	0.58 $\pm$ 0.10	* $\pm$ *	0.67 $\pm$ 0.08	*	*	3	9.54074e+00	*	*
39835	0.3414	* $\pm$ *	1.77 $\pm$ 0.25	* $\pm$ *	* $\pm$ *	*	*	3	1.06062e+01	*	*
36295	0.3544	1.69 $\pm$ 0.13	1.29 $\pm$ 0.11	6.49 $\pm$ 0.30	2.17 $\pm$ 0.14	-17.17	-46.96	2	9.54282e+00	8.87766e+00	4.35738e-01
34216	0.3423	6.24 $\pm$ 0.20	6.94 $\pm$ 0.25	30.00 $\pm$ 0.70	2.97 $\pm$ 0.13	-16.80	-98.30	2	9.79627e+00	8.65666e+00	3.35975e+00
30749	0.3419	1.96 $\pm$ 0.12	4.73 $\pm$ 0.14	7.85 $\pm$ 0.26	0.86 $\pm$ 0.10	-16.51	-71.76	2	9.66567e+00	8.56345e+00	7.18600e-01
30569	0.3421	3.39 $\pm$ 0.12	3.64 $\pm$ 0.20	17.55 $\pm$ 0.10	7.12 $\pm$ 0.40	-19.00	-52.13	1	9.75156e+00	8.85511e+00	2.71330e+00
29643	0.3413	* $\pm$ *	* $\pm$ *	0.60 $\pm$ 0.07	* $\pm$ *	*	-1.94	3	9.50817e+00	*	*
38761	0.3530	3.24 $\pm$ 0.30	3.65 $\pm$ 0.06	48.65 $\pm$ 0.50	15.95 $\pm$ 0.10	-3.23	-49.40	1	1.05592e+01	8.88975e+00	2.65597e+01
42215	0.3513	* $\pm$ *	* $\pm$ *	0.54 $\pm$ 0.10	* $\pm$ *	*	*	3	9.56973e+00	*	*
41326	0.3562	0.71 $\pm$ 0.09	1.76 $\pm$ 0.11	2.64 $\pm$ 0.22	1.53 $\pm$ 0.30	-6.23	-41.03	1	9.21085e+00	8.82265e+00	2.46944e-01
40987	0.3557	1.33 $\pm$ 0.17	2.09 $\pm$ 0.13	9.30 $\pm$ 0.30	3.90 $\pm$ 0.18	-13.82	-41.82	1	9.77601e+00	8.81371e+00	3.78730e+00
40486	0.3389	* $\pm$ *	0.45 $\pm$ 0.10	0.64 $\pm$ 0.20	0.44 $\pm$ 0.05	-11.21	-4.23	2	9.29080e+00	*	*
40205	0.3592	* $\pm$ *	1.32 $\pm$ 0.42	1.30 $\pm$ 0.24	3.96 $\pm$ 0.40	*	-2.87	2	1.06945e+01	*	*
39962	0.3435	0.83 $\pm$ 0.14	2.11 $\pm$ 0.20	2.89 $\pm$ 0.25	0.42 $\pm$ 0.15	-23.47	-69.72	1	8.99402e+00	8.58900e+00	5.31696e-01
39777	0.3433	* $\pm$ *	* $\pm$ *	2.01 $\pm$ 0.34	2.30 $\pm$ 0.80	*	*	3	9.33859e+00	*	*
33486	0.3354	1.52 $\pm$ 0.22	1.05 $\pm$ 0.10	27.00 $\pm$ 0.40	9.62 $\pm$ 0.80	-5.35	-35.73	1	1.03528e+01	8.93986e+00	3.65613e+01
29599	0.3501	0.11 $\pm$ 0.03	0.28 $\pm$ 0.03	0.21 $\pm$ 0.10	* $\pm$ *	-2.94	-7.67	2	9.41494e+00	*	2.00250e-03
27269	0.3396	1.45 $\pm$ 0.12	1.60 $\pm$ 0.10	9.61 $\pm$ 0.10	4.75 $\pm$ 0.40	-11.27	-56.30	1	9.88972e+00	8.89119e+00	2.84404e+00
39280	0.3417	* $\pm$ *	* $\pm$ *	* $\pm$ *	* $\pm$ *	*	*	3	8.83879e+00	*	*
25503	0.3354	1.24 $\pm$ 0.14	1.13 $\pm$ 0.10	18.00 $\pm$ 0.50	7.70 $\pm$ 0.20	-5.12	-36.10	1	1.03307e+01	8.92899e+00	1.42731e+01
21304	0.3497	1.07 $\pm$ 0.10	3.88 $\pm$ 0.10	4.34 $\pm$ 0.10	0.30 $\pm$ 0.10	-20.00	-74.93	2	8.90241e+00	8.43908e+00	2.55343e-01
27355	0.3346	5.63 $\pm$ 0.30	11.05 $\pm$ 0.05	25.60 $\pm$ 0.60	15.85 $\pm$ 1.20	-14.44	-70.24	1	1.13319e+01	8.83589e+00	2.76093e+00
27150	0.3419	0.91 $\pm$ 0.06	* $\pm$ *	4.33 $\pm$ 0.30	2.08 $\pm$ 0.21	-8.66	-73.54	2	9.43506e+00	*	5.66416e-01
26634	0.3455	1.32 $\pm$ 0.11	2.12 $\pm$ 0.03	7.57 $\pm$ 0.13	1.83 $\pm$ 0.30	-11.78	-44.79	2	9.78325e+00	8.73836e+00	*
25902	0.3456	2.94 $\pm$ 0.08	5.81 $\pm$ 0.10	14.70 $\pm$ 0.60	3.90 $\pm$ 0.45	-13.38	-50.36	2	9.77705e+00	8.71905e+00	1.81135e+00
25335	0.3502	* $\pm$ *	* $\pm$ *	* $\pm$ *	* $\pm$ *	*	*	3	9.55409e+00	*	*
24465	0.3483	0.89 $\pm$ 0.08	0.71 $\pm$ 0.20	3.59 $\pm$ 0.15	1.92 $\pm$ 0.33	-24.99	-58.55	1	9.70361e+00	8.93018e+00	3.35147e+00
24050	0.3476	3.77 $\pm$ 0.11	17.25 $\pm$ 0.05	23.00 $\pm$ 1.00	2.15 $\pm$ 0.26	-24.59	-137.5	1	9.29994e+00	8.44528e+00	6.72129e+00
22537	0.3467	1.14 $\pm$ 0.08	2.84 $\pm$ 0.11	3.82 $\pm$ 0.10	0.99 $\pm$ 0.20	-15.17	-71.20	2	9.16245e+00	8.68057e+00	1.76258e-01
21363	0.3371	3.10 $\pm$ 0.12	6.70 $\pm$ 0.17	11.60 $\pm$ 0.03	2.18 $\pm$ 0.27	-15.74	-77.54	2	9.24288e+00	8.65482e+00	5.67027e-01
16098	0.3477	0.23 $\pm$ 0.30	1.80 $\pm$ 0.50	1.72 $\pm$ 0.13	* $\pm$ *	-3.63	-45.69	3	9.29566e+00	*	*
16334	0.3314	0.87 $\pm$ 0.19	1.67 $\pm$ 0.10	8.15 $\pm$ 0.08	4.76 $\pm$ 0.11	-11.82	-40.63	2	9.77613e+00	8.83607e+00	3.68923e+00

Galaxy ID	z	$F(H\beta)$	$F([OIII])$	$F(H\alpha)$	$F([NII])$	$EW_{H\beta}$	$EW_{H\alpha}$	f	$\log(M \ M_{\odot})$	$12 + \log(O/H)$	SFR/Gyr^{-1}
67251	0.3320	0.91 ±0.02	1.37 ±0.07	2.86 ±0.05	0.96 ±0.01	-30.78	-61.60	2	8.66973e+00	8.77436e+00	1.54652e-01
66697	0.3488	3.86 ±0.23	5.86 ±0.12	17.00 ±0.50	5.15 ±0.30	-9.31	-53.83	1	9.83523e+00	8.78483e+00	1.24015e+00
54684	0.3457	* ± *	0.24 ±0.18	* ± *	* ± *	*	*	3	1.00925e+01	*	*
54256	0.3437	* ± *	* ± *	* ± *	* ± *	*	*	3	9.68883e+00	*	*
53830	0.3357	4.19 ±0.05	7.02 ±0.20	15.45 ±0.30	3.30 ±0.03	-18.60	-86.77	1	9.24664e+00	8.70453e+00	6.71088e-01
52509	0.3434	0.43 ±0.02	0.13 ±0.10	2.04 ±0.20	0.55 ±0.20	-5.66	-22.39	1	9.49494e+00	9.01319e+00	1.23355e-01
50611	0.3402	0.26 ±0.06	0.57 ±0.04	0.92 ±0.03	0.90 ±0.10	-49.78	-35.28	2	8.75911e+00	8.86567e+00	4.51975e-02
50288	0.3494	* ± *	0.22 ±0.02	* ± *	* ± *	*	*	3	9.54269e+00	*	*
50088	0.3433	0.82 ±0.12	1.51 ±0.02	3.05 ±0.17	0.34 ±0.07	-17.35	-60.21	1	8.48364e+00	8.60241e+00	3.29639e-03
49673	0.3526	0.16 ±0.01	0.50 ±0.05	1.72 ±0.20	0.65 ±0.09	-2.62	-27.42	1	9.38502e+00	8.78247e+00	3.44921e-01
49437	0.3464	* ± *	* ± *	* ± *	* ± *	*	*	3	9.28509e+00	*	*
47993	0.3428	* ± *	* ± *	* ± *	* ± *	*	*	3	9.63050e+00	*	*
64627	0.3554	1.30 ±0.18	6.06 ±0.11	6.24 ±0.27	0.97 ±0.06	-60.71	-362.0	1	8.71040e+00	8.50408e+00	1.68481e-01
65223	0.3452	0.20 ±0.05	* ± *	0.52 ±0.07	0.29 ±0.03	-1.36	-2.98	2	9.77992e+00	*	3.79763e-03
56746	0.3564	0.42 ±0.06	0.35 ±0.02	1.17 ±0.07	0.44 ±0.04	-19.23	-24.06	1	9.51583e+00	8.87957e+00	1.80582e-01
59958	0.3561	1.84 ±0.10	5.74 ±0.06	10.55 ±0.50	1.24 ±0.10	-14.61	-80.74	1	9.35825e+00	8.54030e+00	4.29372e+00
59728	0.3400	3.65 ±0.17	9.22 ±0.18	14.80 ±0.30	2.70 ±0.21	-16.70	-89.43	1	9.43799e+00	8.62773e+00	1.20510e+00
49813	0.3352	0.71 ±0.05	2.12 ±0.13	3.01 ±0.14	0.51 ±0.07	-7.84	-49.23	1	8.78925e+00	8.61440e+00	2.61656e-01
49541	0.3540	0.19 ±0.05	0.32 ±0.10	2.52 ±0.40	1.28 ±0.06	-2.28	-14.52	2	1.00160e+01	8.92012e+00	*
49281	0.3477	0.45 ±0.08	0.25 ±0.17	* ± *	* ± *	-3.03	*	3	9.84710e+00	*	*
47707	0.3463	* ± *	1.83 ±0.19	18.50 ±1.30	11.73 ±1.10	*	-20.44	2	1.05461e+01	*	*
46905	0.3509	0.17 ±0.10	1.21 ±0.08	1.89 ±0.15	0.69 ±0.05	-2.91	-24.64	1	8.90565e+00	8.65568e+00	4.64329e-01
46562	0.3414	* ± *	* ± *	* ± *	* ± *	*	*	3	1.00692e+01	*	*
44177	0.3523	1.48 ±0.08	3.33 ±0.09	3.97 ±0.14	0.75 ±0.29	-13.82	-39.60	1	9.26487e+00	8.65301e+00	9.83807e-02
41819	0.3424	0.95 ±0.02	3.18 ±0.13	3.33 ±0.10	0.65 ±0.04	-82.81	-158.9	2	8.34022e+00	8.57999e+00	1.79270e-01
36894	0.3440	1.29 ±0.11	0.96 ±0.09	5.89 ±0.15	1.78 ±0.16	-7.71	-43.56	1	9.31200e+00	8.89043e+00	4.56438e-01
36701	0.3417	* ± *	* ± *	* ± *	* ± *	*	*	3	9.22086e+00	*	*
32268	0.3491	0.35 ±0.09	0.23 ±0.04	2.04 ±0.20	0.94 ±0.20	-6.57	-30.23	1	8.94965e+00	8.97294e+00	2.25245e-01
46037	0.3370	2.25 ±0.12	3.45 ±0.14	9.11 ±0.50	4.22 ±0.33	-16.62	-88.18	2	9.26929e+00	8.82671e+00	5.61951e-01
45796	0.3374	0.98 ±0.32	1.06 ±0.15	* ± *	3.59 ±0.40	-12.92	*	2	9.42293e+00	*	*
43489	0.3490	* ± *	0.77 ±0.08	* ± *	* ± *	*	-5.69	3	9.55616e+00	*	*
42003	0.3359	* ± *	* ± *	* ± *	* ± *	*	*	3	9.31975e+00	*	*
40467	0.3395	0.35 ±0.02	1.02 ±0.09	1.91 ±0.09	* ± *	-92.75	-168.9	2	8.58872e+00	*	*
40034	0.3550	* ± *	* ± *	* ± *	* ± *	*	*	3	1.04381e+01	*	*
39879	0.3529	* ± *	* ± *	* ± *	* ± *	*	*	3	9.28143e+00	*	*
33948	0.3360	0.62 ±0.03	0.56 ±0.04	* ± *	2.55 ±0.70	-10.18	*	3	9.35065e+00	*	*

Galaxy ID	z	$F(H\beta)$	$F([OIII])$	$F(H\alpha)$	$F([NII])$	$EW_{H\beta}$	$EW_{H\alpha}$	f	$\log(M \ M_{\odot})$	$12 + \log(O/H)$	SFR/Gyr^{-1}
32196	0.3455	* $\pm$ *	* $\pm$ *	* $\pm$ *	* $\pm$ *	*	*	3	1.06598e+01	*	*
44793	0.3347	* $\pm$ *	* $\pm$ *	15.60 $\pm$ 2.00	* $\pm$ *	*	*	3	1.01829e+01	*	*
38510	0.3397	0.48 $\pm$ 0.05	0.50 $\pm$ 0.05	* $\pm$ *	0.43 $\pm$ 0.04	-5.22	*	2	8.53971e+00	*	*
39501	0.3482	0.59 $\pm$ 0.06	* $\pm$ *	0.88 $\pm$ 0.20	* $\pm$ *	-0.31	-0.44	3	1.09315e+01	*	8.59389e-05
65668	0.3556	0.40 $\pm$ 0.04	1.20 $\pm$ 0.06	2.52 $\pm$ 0.12	* $\pm$ *	-30.99	-161.4	2	8.45363e+00	*	5.45215e-01
57090	0.3442	* $\pm$ *	* $\pm$ *	* $\pm$ *	* $\pm$ *	*	*	3	9.51074e+00	*	*
60961	0.3440	* $\pm$ *	* $\pm$ *	* $\pm$ *	* $\pm$ *	*	*	3	1.05053e+01	*	*
54872	0.3360	* $\pm$ *	0.22 $\pm$ 0.04	0.73 $\pm$ 0.33	0.17 $\pm$ 0.02	*	-13.36	3	8.98943e+00	*	*
53910	0.3522	0.80 $\pm$ 0.20	1.24 $\pm$ 0.20	6.27 $\pm$ 0.29	4.29 $\pm$ 0.30	-10.97	-32.35	1	9.65428e+00	8.88995e+00	3.30711e+00
53311	0.3445	* $\pm$ *	0.23 $\pm$ 0.03	* $\pm$ *	* $\pm$ *	*	*	3	9.03185e+00	*	*
51785	0.3373	0.75 $\pm$ 0.10	1.43 $\pm$ 0.04	2.83 $\pm$ 0.20	0.17 $\pm$ 0.10	-8.29	-39.05	2	8.74673e+00	8.53241e+00	8.77297e-02
51477	0.3478	* $\pm$ *	* $\pm$ *	* $\pm$ *	* $\pm$ *	*	*	3	1.03203e+01	*	*
49908	0.3376	5.74 $\pm$ 0.13	3.25 $\pm$ 0.20	29.05 $\pm$ 0.55	11.45 $\pm$ 0.45	-12.56	-57.03	1	9.73387e+00	8.94943e+00	3.17567e+00
47707	0.3466	0.56 $\pm$ 0.20	1.80 $\pm$ 0.18	31.10 $\pm$ 2.00	14.30 $\pm$ 0.50	-0.96	-32.92	2	1.05461e+01	8.89669e+00	4.79433e+01
65718	0.3344	1.42 $\pm$ 0.15	3.48 $\pm$ 0.10	6.09 $\pm$ 0.21	1.34 $\pm$ 0.12	-10.93	-53.39	1	9.53968e+00	8.66873e+00	4.93558e-01
66734	0.3538	* $\pm$ *	* $\pm$ *	1.78 $\pm$ 0.15	1.53 $\pm$ 0.20	*	-7.63	3	9.93175e+00	*	*
67452	0.3429	0.57 $\pm$ 0.10	0.63 $\pm$ 0.19	6.18 $\pm$ 0.30	2.85 $\pm$ 0.50	-6.16	-40.47	1	1.02076e+01	8.90367e+00	6.33336e+00
59303	0.3534	0.67 $\pm$ 0.04	0.45 $\pm$ 0.06	0.95 $\pm$ 0.10	0.14 $\pm$ 0.01	-56.03	-28.49	1	8.94532e+00	8.76645e+00	3.30963e-02
53600	0.3439	2.13 $\pm$ 0.13	4.61 $\pm$ 0.18	8.75 $\pm$ 0.32	1.01 $\pm$ 0.17	-13.85	-126.5	1	9.27725e+00	8.58989e+00	6.83108e-19
52439	0.3460	2.46 $\pm$ 0.08	6.71 $\pm$ 0.17	9.65 $\pm$ 0.30	1.38 $\pm$ 0.24	-17.87	-87.33	2	9.44181e+00	8.58183e+00	1.05603e+00
51198	0.3456	1.14 $\pm$ 0.23	2.60 $\pm$ 0.30	2.19 $\pm$ 0.10	1.02 $\pm$ 0.50	-32.74	-127.1	2	8.73858e+00	8.76141e+00	6.05638e-02
51349	0.3546	0.81 $\pm$ 0.10	0.73 $\pm$ 0.08	3.20 $\pm$ 0.19	1.03 $\pm$ 0.10	-18.21	-43.73	3	9.53825e+00	8.84811e+00	*
51067	0.3457	* $\pm$ *	* $\pm$ *	* $\pm$ *	* $\pm$ *	*	*	3	9.58415e+00	*	*
50321	0.3444	0.26 $\pm$ 0.08	0.89 $\pm$ 0.18	2.06 $\pm$ 0.30	0.32 $\pm$ 0.10	-86.81	-57.90	1	8.68897e+00	8.54492e+00	8.94074e-01
49610	0.3451	0.49 $\pm$ 0.03	0.61 $\pm$ 0.10	2.99 $\pm$ 0.15	0.64 $\pm$ 0.16	-10.26	-66.28	2	9.40653e+00	8.76074e+00	*
48549	0.3421	1.36 $\pm$ 0.13	0.89 $\pm$ 0.16	9.68 $\pm$ 0.30	* $\pm$ *	-3.80	-31.84	2	9.99824e+00	*	1.21356e+00
47759	0.3435	0.76 $\pm$ 0.13	0.70 $\pm$ 0.12	4.83 $\pm$ 0.13	1.57 $\pm$ 0.25	-5.81	-52.32	1	9.64962e+00	8.88311e+00	1.57863e+00
47559	0.3528	1.28 $\pm$ 0.10	3.47 $\pm$ 0.14	5.11 $\pm$ 0.38	2.91 $\pm$ 0.40	-13.94	-47.01	1	9.33361e+00	8.78024e+00	3.96449e-01
54743	0.3484	0.96 $\pm$ 0.10	1.99 $\pm$ 0.10	2.86 $\pm$ 0.11	1.06 $\pm$ 0.24	-32.68	-76.85	2	8.67976e+00	8.74296e+00	1.55473e-01
45076	0.3487	* $\pm$ *	* $\pm$ *	* $\pm$ *	* $\pm$ *	*	*	3	9.53934e+00	*	*
39910	0.3537	1.42 $\pm$ 0.10	4.89 $\pm$ 0.16	5.60 $\pm$ 0.10	0.61 $\pm$ 0.12	-21.21	-111.6	3	8.58655e+00	8.50842e+00	*
33424	0.3490	2.09 $\pm$ 0.05	7.13 $\pm$ 0.07	7.42 $\pm$ 0.10	2.20 $\pm$ 0.10	-11.42	-58.17	3	9.06624e+00	8.66292e+00	*
32814	0.3496	* $\pm$ *	* $\pm$ *	* $\pm$ *	* $\pm$ *	*	*	3	9.86077e+00	*	*
31699	0.3378	8.16 $\pm$ 0.19	5.42 $\pm$ 0.40	52.00 $\pm$ 1.00	16.00 $\pm$ 0.20	-5.46	-64.60	1	1.00281e+01	8.92391e+00	*
36710	0.3412	* $\pm$ *	* $\pm$ *	* $\pm$ *	* $\pm$ *	*	*	3	1.02613e+01	*	*
37522	0.3498	* $\pm$ *	* $\pm$ *	* $\pm$ *	* $\pm$ *	*	*	3	1.09483e+01	*	*

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38510	0.3385	* ± *	* ± *	* ± *	* ± *	*	*	3	8.53971e+00	*	*
39357	0.3517	* ± *	* ± *	* ± *	* ± *	*	*	3	1.05143e+01	*	*
44418	0.3519	0.60 ±0.15	2.25 ±0.06	2.91 ±0.10	1.99 ±0.22	-23.77	-80.65	2	8.57065e+00	8.75002e+00	3.84926e-01
44255	0.3491	* ± *	0.56 ±0.08	* ± *	* ± *	*	*	3	9.54346e+00	*	*
41442	0.3438	1.10 ±0.02	4.54 ±0.16	11.40 ±0.30	3.27 ±0.18	-2.94	-43.14	1	9.66407e+00	8.69717e+00	2.16957e+00
40200	0.3467	* ± *	* ± *	* ± *	1.44 ±0.07	*	-0.53	3	1.04357e+01	*	*
39624	0.3522	0.68 ±0.12	1.66 ±0.18	5.40 ±0.50	4.35 ±0.50	-16.64	-88.62	2	8.54984e+00	8.83895e+00	1.61687e+00
38551	0.3522	1.64 ±0.10	1.44 ±0.17	8.69 ±0.18	2.48 ±0.14	-13.33	-63.25	1	9.66498e+00	8.84202e+00	2.54783e+00
36059	0.3543	0.48 ±0.05	0.67 ±0.04	2.27 ±0.10	3.56 ±0.28	-5.23	-26.48	2	9.58323e+00	9.04920e+00	2.01258e-01
35903	0.3333	1.38 ±0.09	4.35 ±0.09	3.93 ±0.18	0.95 ±0.05	-33.01	-40.39	2	9.09203e+00	8.62520e+00	1.29730e-01
34028	0.3524	3.65 ±0.25	19.10 ±0.20	12.85 ±0.15	0.59 ±0.08	-107.0	-358.2	2	8.65426e+00	8.31567e+00	1.30426e+00
32469	0.3424	0.78 ±0.04	1.10 ±0.05	2.90 ±0.05	* ± *	-10.56	-69.46	2	8.97196e+00	*	1.88289e-01
46445	0.3432	* ± *	* ± *	* ± *	* ± *	*	*	3	9.76288e+00	*	*
42109	0.3424	4.79 ±0.18	9.88 ±0.18	43.90 ±0.90	25.10 ±0.60	-9.94	-91.64	2	1.01293e+01	8.82835e+00	*
42032	0.3409	* ± *	0.15 ±0.00	0.40 ±0.05	* ± *	*	-6.63	2	8.97500e+00	*	*
40758	0.3506	* ± *	* ± *	* ± *	1.37 ±0.21	*	-6.35	3	9.20202e+00	*	*
34226	0.3384	* ± *	* ± *	* ± *	* ± *	*	*	3	9.71274e+00	*	*
33447	0.3552	0.25 ±0.03	0.50 ±0.05	* ± *	* ± *	-9.21	-17.92	3	9.15144e+00	*	*
33193	0.3488	* ± *	* ± *	* ± *	* ± *	*	*	3	9.22435e+00	*	*
32894	0.3347	3.53 ±0.20	3.82 ±0.09	14.05 ±0.20	3.64 ±0.30	-9.68	-66.18	1	9.70776e+00	8.80884e+00	1.31088e+00
31639	0.3480	* ± *	* ± *	* ± *	* ± *	*	*	3	9.33671e+00	*	*
31432	0.3436	3.26 ±0.20	8.64 ±0.12	13.70 ±0.60	3.89 ±0.80	-11.68	-66.30	1	9.45072e+00	8.69135e+00	8.50759e-01
31109	0.3397	* ± *	* ± *	* ± *	* ± *	*	*	3	1.02671e+01	*	*
29422	0.3399	5.48 ±0.28	4.26 ±0.25	22.70 ±0.50	7.08 ±0.06	-16.24	-91.08	1	9.42487e+00	8.86664e+00	1.30614e+00
27857	0.3557	0.72 ±0.06	1.61 ±0.09	2.35 ±0.10	* ± *	-6.31	-27.47	2	9.20330e+00	*	7.18438e-02
27443	0.3383	0.45 ±0.05	0.78 ±0.12	1.08 ±0.07	0.14 ±0.10	-9.25	-37.42	2	8.46411e+00	8.64866e+00	1.66444e-02
27060	0.3367	0.73 ±0.06	1.08 ±0.06	2.66 ±0.08	0.76 ±0.10	-11.57	-56.23	2	9.04846e+00	8.77332e+00	1.57332e-01
36451	0.3365	0.92 ±0.09	3.33 ±0.11	4.11 ±0.10	0.22 ±0.15	-14.81	-88.78	2	8.59087e+00	8.41251e+00	3.43129e-01
37949	0.3534	* ± *	* ± *	* ± *	* ± *	*	*	3	1.02029e+01	*	*
38246	0.3512	* ± *	0.48 ±0.04	* ± *	1.22 ±0.15	*	*	3	1.02939e+01	*	*
41973	0.3530	0.88 ±0.40	3.12 ±0.12	2.68 ±0.20	0.44 ±0.06	-233.3	-201.1	1	8.46239e+00	8.54478e+00	1.01247e-01
41713	0.3446	* ± *	* ± *	* ± *	* ± *	*	*	3	9.23997e+00	*	*
40281	0.3531	1.18 ±0.20	3.87 ±0.07	5.64 ±0.20	0.63 ±0.04	-23.49	-84.82	1	9.24721e+00	8.51702e+00	8.55185e-01
37861	0.3514	0.27 ±0.07	0.43 ±0.02	1.68 ±0.11	* ± *	-4.30	-56.15	2	8.74298e+00	*	2.39248e-01
37631	0.3525	0.68 ±0.13	1.13 ±0.10	3.71 ±0.19	1.73 ±0.27	-8.62	-51.20	1	9.36494e+00	8.83490e+00	1.00349e+00
36817	0.3479	1.09 ±0.10	3.37 ±0.12	3.45 ±0.30	0.20 ±0.03	-45.33	-100.2	1	8.78930e+00	8.42627e+00	2.28825e-01

Galaxy ID	z	$F(H\beta)$	$F([OIII])$	$F(H\alpha)$	$F([NII])$	$EW_{H\beta}$	$EW_{H\alpha}$	f	$\log(M \ M_{\odot})$	$12 + \log(O/H)$	SFR/Gyr^{-1}
35131	0.3418	0.60 ±0.05	1.96 ±0.10	3.10 ±0.20	1.65 ±0.13	-5.99	-49.83	2	9.22950e+00	8.77404e+00	3.87210e-01
33812	0.3467	11.55 ±2.00	9.46 ±0.40	44.55 ±0.50	26.90 ±1.40	-14.24	-82.42	2	1.10986e+01	8.95420e+00	*
32712	0.3424	* ± *	0.27 ±0.01	* ± *	* ± *	*	*	3	9.47240e+00	*	*
31856	0.3364	0.65 ±0.07	0.76 ±0.04	2.68 ±0.30	0.97 ±0.03	-10.32	-52.93	1	8.67142e+00	8.84250e+00	1.78961e-01
31409	0.3457	* ± *	* ± *	* ± *	* ± *	*	*	3	1.00692e+01	*	*
31168	0.3479	2.89 ±0.19	10.40 ±0.30	11.10 ±0.40	1.75 ±0.20	-55.67	-180.9	1	8.86396e+00	8.54260e+00	8.75044e-01
30880	0.3422	1.45 ±0.15	1.47 ±0.40	8.66 ±0.30	2.51 ±0.21	-6.27	-29.53	1	1.02089e+01	8.85033e+00	2.47597e+00
30709	0.3497	1.09 ±0.11	2.09 ±0.12	2.66 ±0.20	* ± *	-33.30	-107.6	2	8.35639e+00	*	1.58573e-01
30398	0.3561	2.35 ±0.13	3.60 ±0.30	8.88 ±0.90	* ± *	-8.90	-40.84	2	9.79633e+00	*	5.23049e-01
28704	0.3425	2.61 ±0.16	1.09 ±0.12	34.60 ±0.90	8.49 ±0.90	-4.09	-39.38	1	1.08728e+01	8.97255e+00	2.67267e+01
27069	0.3373	7.06 ±0.18	23.85 ±0.25	22.85 ±0.25	2.50 ±0.20	-86.64	-261.3	1	8.83157e+00	8.49805e+00	1.66584e+00
26430	0.3458	0.92 ±0.15	1.53 ±0.20	3.07 ±0.23	0.27 ±0.08	-15.29	-84.63	1	8.77924e+00	8.58636e+00	2.14971e-01
22712	0.3462	* ± *	0.36 ±0.02	* ± *	* ± *	*	*	3	9.59816e+00	*	*
21640	0.3424	* ± *	0.90 ±0.18	* ± *	* ± *	*	*	3	9.20647e+00	*	*
19720	0.3411	0.25 ±0.02	1.53 ±0.09	2.01 ±0.10	0.65 ±0.20	-12.79	-48.65	1	9.23616e+00	8.59020e+00	1.96430e+00
19261	0.3486	2.09 ±0.20	2.43 ±0.07	2.45 ±0.13	0.88 ±0.13	-19.65	-29.86	1	9.67622e+00	8.82634e+00	2.90762e-02
18885	0.3444	* ± *	* ± *	* ± *	* ± *	*	*	3	1.01299e+01	*	*
18505	0.3463	* ± *	* ± *	* ± *	* ± *	*	*	3	1.00831e+01	*	*
16865	0.3451	0.57 ±0.10	1.18 ±0.08	1.22 ±0.07	0.60 ±0.05	-19.65	-54.22	2	8.38243e+00	8.78883e+00	2.95135e-02
14674	0.3555	2.73 ±0.20	3.68 ±0.32	38.70 ±0.40	17.80 ±1.00	-2.56	-36.04	1	1.10045e+01	8.92836e+00	2.18612e+01
12395	0.3544	0.50 ±0.02	0.76 ±0.01	3.49 ±0.11	1.17 ±0.16	-2.46	-13.61	1	1.00906e+01	8.87073e+00	4.56262e-01
12111	0.3539	1.50 ±0.09	1.96 ±0.07	10.60 ±0.30	2.27 ±0.28	-8.54	-93.78	1	9.42741e+00	8.76050e+00	2.05849e+00
23089	0.3445	1.25 ±0.15	0.22 ±0.06	8.72 ±0.14	3.39 ±0.40	-22.12	-83.35	1	1.02813e+01	9.09781e+00	8.72805e+00
21643	0.3502	0.75 ±0.10	2.01 ±0.20	4.13 ±0.40	4.06 ±0.40	-6.46	-75.16	2	9.11674e+00	8.88419e+00	4.89189e-01
20460	0.3537	2.36 ±0.17	3.22 ±0.35	21.70 ±0.90	5.66 ±0.70	-6.87	-58.86	1	1.03084e+01	8.79041e+00	1.36609e+01
19985	0.3496	1.73 ±0.12	2.42 ±0.14	13.20 ±0.40	6.96 ±0.30	-6.14	-52.37	2	9.95982e+00	8.88969e+00	2.93075e+00
19936	0.3338	0.77 ±0.08	2.38 ±0.07	3.15 ±0.20	0.54 ±0.10	-35.34	-203.2	2	8.61226e+00	8.57940e+00	3.58440e-01
19173	0.3333	2.11 ±0.14	1.41 ±0.14	19.00 ±0.70	8.61 ±0.40	-8.63	-56.56	2	1.01707e+01	8.95748e+00	8.71084e+00
17343	0.3490	1.40 ±0.10	4.04 ±0.10	5.19 ±0.13	2.75 ±0.18	-32.25	-138.4	1	8.98501e+00	8.74681e+00	4.02363e-01
16148	0.3500	7.52 ±0.28	14.10 ±0.20	26.30 ±0.50	5.08 ±0.40	-22.69	-102.3	2	9.56558e+00	8.67139e+00	1.66739e+00
14744	0.3472	0.59 ±0.03	2.35 ±0.10	3.13 ±0.17	2.70 ±0.50	-13.99	-111.5	2	8.92343e+00	8.78439e+00	7.47846e-01
13342	0.3482	0.18 ±0.06	* ± *	1.62 ±0.08	0.91 ±0.10	-3.17	-15.27	2	9.78074e+00	*	2.78969e-01
16387	0.3501	1.96 ±0.20	1.33 ±0.21	20.50 ±0.30	14.10 ±0.40	-3.96	-26.65	2	1.03543e+01	9.05025e+00	4.69330e+00
65399	0.3435	1.94 ±0.07	7.39 ±0.30	4.55 ±0.40	0.40 ±0.14	-15.88	-26.53	2	8.97617e+00	8.47027e+00	9.46007e-02
66496	0.3502	* ± *	0.35 ±0.03	* ± *	* ± *	*	*	3	9.27354e+00	*	*

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