Resolving gas-phase metallicity in galaxies

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Introduction

1 Inside-out galaxy growth

In their most basic form galaxies are gravitationally bound environments where gas is converted into stars.

Star forming galaxies generally consist of two discs (gaseous and stellar), embedded in a dark matter halo. Over time, atomic and molecular gas in the gaseous disc will cool, coalesce and collapse under gravity to form stars. Because the stellar disc is built from the gas disc, the two discs are aligned with each other. Note, however, the discs are not the same sizes, with the gas disc usually being the larger of the two (e.g. Broeils & Rhee 1997).

The sizes of the stellar and gas discs are not necessarily static throughout a galaxy's lifetime. Indeed we observe that the centres of galaxies are older (more metal rich) than their younger (metal poor) outskirts (e.g. Sánchez-Blázquez et al. 2014). This implies that historically the star-formation in galaxies was centrally concentrated and has since progressed outwards. This scenario is commonly referred to as the "inside-out" growth of galaxies (Larson 1976) and is in good qualitative agreement with many observations (e.g. Prantzos & Boissier 2000).

However, it remains unclear exactly which mechanisms are responsible for the apparent inside-out growth. To understand this it is important to understand how much of the stellar disc was formed in-situ and how many of the stars were formed in other galaxies that have since merged into the disc. Focusing in particular on the in-situ formation, it is necessarily to understand the connection between the stellar and gaseous discs. We must ask how exactly do galaxies acquire their gas and how it is redistributed within a galaxy. In addition, we must also understand what are the necessary conditions for star-formation and which processes might regulate it.

1.1 Star formation regulation and gas supply

Evidence has indicated that galaxies continue to acquire gas throughout their lives. For example, by measuring the gas contents and star-formation rates of $1 \lesssim z \lesssim 4$ galaxies Tacconi et al. (2013) found that the average galaxy has enough gas the sustain ~ 0.7 Gyr of star formation. While this is long time, it is still substantially shorter than the age of the Universe.

A second interesting result about star-forming galaxies arises if we compare the stellar mass of a galaxy with its star-formation rate (SFR). One observes a correlation between stellar mass and SFR, such that the more massive galaxies are forming stars faster (Whitaker et al. 2012). This mass–SFR correlation is often referred to as the galaxy "main-sequence" (Noeske et al. 2007). However, this term is somewhat erroneous because there is no tight track along which galaxies move, and there is a significant scatter of galaxies about the main sequence (Guo et al. 2013). It is therefore important to ask what drives the scatter in the main sequence, i.e. what determines a galaxy's SFR.

Firstly, the environment that surrounds a galaxy is likely to influence its SFR. Galaxies that live in low density environments may not acquire as much gas, consequently this may cause these galaxies to fall below the main sequence. In denser environments, not only might galaxies receive more gas, but encounters with other galaxies may be more frequent. These interactions could also enhance the SFR of galaxies (Barton et al. 2000).

However, there are potential mechanisms that could dampen these effects. Indeed the act of forming stars may produce negative feedback that inhibits the further production of stars (Silk 1997). For example, supernovae may cause turbulence that prevents gas clouds from collapsing and forming stars (e.g. Dib et al. 2006). There is good evidence that star formation is quite inefficient and negative feedback processes are often thought to play in important part in regulating the star-formation in galaxies. Feedback may act as a damping or restorative force that governs the SFR of galaxies, thus ensuring they remain close to the main sequence (Davé et al. 2012).

As we have just discussed, the gas supply and regulation of star formation in galaxies are some of the key concepts in field of galaxy evolution today. As such, there are a few overarching questions that motivate this thesis:

- How do galaxies acquire the gas? What roles might gas inflows and outflows play in achieving or inhibiting this?
- What factors govern the star-formation rates of galaxies? Is star-formation regulated on local scales within a galaxy or is it regulated by a galaxy's global properties?
- How much are the properties of a galaxy by determined by itself (internal processes) and how much by environment in which it lives (external factors)?

Naturally complete answers these questions are beyond any single thesis. This thesis focus on what we can learn from the gas-phase metallicity of galaxies.

2 Gas-phase metallicity

To understand galaxies one should not only studying the amount of gas in galaxies, but one should also study its metallicity.

Metallicity is power diagnostic with which we can learn about the history of the gas. Gas that has resided in galaxies for a long period will be heavily polluted with metals (e.g. from supernova ejecta), whereas gas that has been recently acquired from outside the galaxy should be relatively pristine. Simply stated, we can use gas-phase metallicity[1] to infer inflows of gas into galaxies.

However, inflows are not the only mechanism than can lower the metallicity of a galaxy. In fact outflowing gas will also produce a similar signature (Tremonti et al. 2004). It is this degeneracy between inflows and outflows that makes interpreting the metallicity of galaxies challenging.

Clearly gas-phase metallicity is not a panacea for understanding galaxy evolution. But, there are a few ways in which we can break this degeneracy. First and foremost metallicity should be studied in conjunction with other galaxy properties (e.g. stellar mass, star-formation rate). Chemical evolution models of galaxies suggest that metallicity exists in a dynamic equilibrium with these properties (Lilly et al. 2013), where it is essentially the balance of inflows and outflows that governs this equilibrium. Such models provide leverage for interpreting the roles of inflows and outflows. However, such models by themselves cannot address all the questions

[1]Unless otherwise stated, herein we will use (gas-phase) metallicity to refer to the oxygen abundance of the interstellar medium.

on the nature of such processes. Therefore we also need to spatially resolve the metallicity in galaxies to understand the physical scales on which these mechanisms exist.

2.1 Measuring gas-phase metallicity

So we have yet to explain how one measures the gas-phase metallicity of galaxies. Here we will briefly outline how metallicity (oxygen abundance) can be measured from rest-frame optical spectra of H II regions[2].

The temperature and the emitted emission-lines of H II regions are dependent on the elemental abundances of the interstellar gas. As a result these luminous star-forming regions can be used to probe the metallicity of the interstellar medium in nearby and distant galaxies.

If we are able to measure the physical properties of the gas (e.g. temperature and density) then we can calculate the intrinsic emissivity of different ionic species. Inder some simplifying assumptions, knowing the both observed emission-line ratios and the intrinsic emissivity ratios one can compute the abundance of the ionic species and, by extension, the metallicity.

2.1.1 The link between metallicity and temperature

Perhaps the most important physical property that metallicity affects is the temperature of gas. The reason for this is as follows. H II regions exist in a temperature equilibrium where heating is balanced by the cooling. The heating is provided by the photons emitted by the central star which ionizes the gas, ejecting electrons with some characteristic temperature. These electrons can subsequently recombine and, in theory, allow the gas to cool.

However, the recombination photons have a high probability to be reabsorbed and are unlikely to escape the H II regions. Recombination is ireportnefficient at allowing the gas to cool. In contrast, forbidden emission-line photons have a low probability of be reabsorbed, providing an efficient cooling mechanism. The upper levels of forbidden emission-line transitions can be populated by collisional excitation between metal ions and electrons.

So in theory the more metals in the gas, the greater the cooling efficiency. However, since the heating and cooling rates must balance, the increased cooling efficiency is compensated by a reduced electron temperature. This is because a reduction in the temperature reduces the collisional excitation rate, and thus reduces the forbidden emission-line flux. For this reason metallicity and temperature are closely related properties of H II regions, the higher the metallicity the lower the temperature (e.g. Wiersma et al. 2009)

2.1.2 The Direct method (T_e method)

If we wish to measure ionic abundances we need to know the intrinsic emissivities of the ions. To calculate the emissivity we must measure both the electron temperature and the electron density of the gas.

Electron densities can be inferred from density sensitive emission-line ratios, e.g. [O II]3729/[O II]3726 and [S II]6731/[S II]6717. These emission-lines are typically bright and can be easily observed if they fall within the wavelength range of the spectrum. Typically one assumes that the electron density is constant throughout the H II region.

In contrast, measuring the electron temperature is more difficult (there is no single electron temperature for the whole H II region). Because different ionic species are found at different radii, different species have different characteristic electron temperatures.

For example, the zone containing O^{2+} (which is close to the star) is typically hotter than the O^{+} zone (Izotov et al. 2006). To calculate the emissivities of these O^{2+} and O^{+} zones, we

[2]Regions of ionized gas that surrounding young, hot O and B type stars

must measure the temperatures in both. In the case of O^{2+} we can use emission-line ratios such as [O III]4363/[O III]5007, and in the case of O^{+} states we can use [O II]3727/[O III]7320,7330. In most H II regions there is a negligible amount of O^{3+} (and no neutral oxygen), so the oxygen abundance can be derived by adding up the abundances of O^{2+} and O^{+}.

While it is ideal to measure the oxygen abundance (metallicity) in this way, the [O III]4363 and [O III]7320,7330 lines are relatively faint. So this "direct" method can only be applied to H II regions within the Milky Way and other nearby galaxies. For distant galaxies we must use another technique that uses only the bright (strong) emission-lines.

2.1.3 Strong-line methods

In distant galaxies we are often limited to using only the brightest emission lines to derive metallicity (e.g. [O II]3726,3729, Hβ, [O III]5007, Hα, [N II]6584 and [S II]6717,6731). While these lines do not provide useful diagnostics to *directly* infer the electron temperatures, they do nonetheless encode information on the metallicity.

There are a variety of methods that fall under the category of strong-line methods, exploiting different combinations of emission-lines to derive the metallicity (each with its own benefits and disadvantage). However, in general strong-line methods can be divided into two types. Those that are empirically calibrated to observed H II regions, and those that use theoretical photoionization models to calculate the metallicity. We shall now briefly discuss the relative merits of both the empirical and the theoretical approaches.

Empirical methods use nearby H II regions where metallicities have been derived using the direct method. With these observations the strong emission-lines can then be calibrated as a function of metallicity. The advantage of this approach is that one need not understand the underlying physics of H II regions to derive metallicities from the strong lines. However, there are two main issues with the empirical approach. Firstly, there are very few high-metallicity H II regions with reliable metallicity determinations. This is because at super-solar metallicities (low temperatures) the [O III]4363 emission-line is very faint. It is therefore questionable how reliable empirical calibrations are at high-metallicities. The second issue is that fundamentally we must assume that the H II regions in distant galaxies are similar to H II regions in the Universe today. Indeed there is good evidence that the conditions have changed, for example it is understood that the density of the interstellar medium was previously higher (Shirazi et al. 2014).

By deriving metallicity from theoretical photoionization models we can avoid both of these limitations/assumptions. Theoretical models do not suffer from the observational biases and they can explore a large portion of the potential parameter space. However, a theoretical approach does have its own limitations. Firstly, by permitting a large unconstrained parameter space there can be degenerate solutions for the metallicity. The empirical methods mitigate against this by encoding natural correlations between parameters, effectively reducing the dimensionally of the parameter space. That is not to say that theoretical methods cannot also encode such information, indeed some methods do (e.g. Pérez-Montero (2014) and that presented in Chapter 3 herein). There is a second concern over using theoretical methods that ultimately the accuracy of the theoretical methods is limited by the accuracy of our photoionization models.

In this thesis we will be studying distant galaxies and as such we must rely upon strong-line methods to derive the metallicities. In particular we will use use those based on theoretical photoionization models.

3 Integral field spectroscopy (IFS)

Technical improvements in astronomical instrumentation have played a crucial role in advancing our knowledge of galaxies. Notably the past few decades has seen the development of integral-field spectrographs, taking spectroscopy to the next dimension. Integral-field spectroscopy (IFS) simultaneously obtains spectra over a 2D field of view (FoV), providing hyperspectral imaging of extended astronomical objects. IFS offers obvious advantages over traditional long-slit spectrographs that only provide a 1D view of the Universe.

Early integral-field spectrographs had significant drawbacks, suffering from a combination of having: a small FoV, poor spatial resolution, limited wavelength coverage, and/or low spectral resolution. However, over time with improvements in instrument design and manufacturing techniques, integral-field spectrographs now offer spectral resolutions and wavelength coverages comparable to traditional long-slit spectrographs. Furthermore some of the latest integral-field spectrographs also provide an image quality (spatial resolution) competitive with imagers.

A large portion of this thesis is based upon work with one instrument in particular: the Multi Unit Spectroscopic Explorer (MUSE; Bacon et al. (2010, and in prep.)). MUSE is a second generation for the Very Large Telecope (VLT) mounted on the Nasmyth focus of the Yepun telescope (UT4). MUSE is an optical integral-field spectrograph which, in Wide Field Mode, offers a $1' \times 1'$ FoV with a $0.2''$ sampling (the resolution is effectively seeing limited). In the spectral dimension MUSE provides a wavelength coverage over 4750Å – 9300Å, with 2.3Å resolution.

On paper MUSE only offers modest technical gains and improvements of existing integral-field spectrographs. This, however, rather belies the true step-change that MUSE affords. Up to now spectrograph have been largely limited to a follow-up capacity. The large FoV and good sensitivity that MUSE affords is sufficient to perform "blind" spectroscopy. This avoids the need for preselection that would otherwise biased us against observing faint and unusual objects .

In this thesis we will use a combination of long-slit (Chapter 2) and IFS techniques (Chapters 3–5) to spatially resolve the gas-phase metallicity of low redshift ($z \sim 0.025$) and intermediate redshift galaxies ($0.1 \lesssim z \lesssim 1$), respectively.

4 This thesis

Chapter 2 Using long-slit spectra we study the metallicity profiles of 50 galaxies ($z \sim 0.025$). These galaxies were selected to have similar stellar masses ($10.2 \lesssim \log_{10}(M_*/M_\odot) \lesssim 11.0$), but span a range of gas masses. This allows us to compare H I-rich galaxies to a control sample of H I-"normal" galaxies.
In previous work by Moran et al. (2012) it was found that in H I-rich galaxies the gas-phase metallicity profile steepens at large radii. They suggested this as evidence for the gas-rich galaxies having recently acquired excess gas that resides at the outermost radii. Our results, however, do not support their conclusions. While we do find galaxies with metallicity profiles steeper in the outer disc than the inner disc, we do not find the same dependency with H I-mass fraction ($M(\text{H I})/M_*$). Outer metallicity drops occur in both H I-rich and H I-normal galaxies. However, even though we do not find these metallicity drops to be correlated with the global (total) gas fraction of the galaxy, we suggest that presence of the metallicity drops are consistent with the local (resolved) gas fraction. Using a simple analytical chemical evolution model we are able to account for the variety of metallicity profiles we observe. This provides a simple interpretation that the metallicity drops occur where the galaxy transitions from a stellar

dominated inner disc, to a gas dominated outer disc. As an important distinction from the work of Moran et al. (2012), this does not necessarily require the gas in the outer disc to have been recently deposited.
Intriguingly the success of the analytical model implies that the metallicity in these galaxies in is dynamic equilibrium with the local conditions. And by extension star-formation is regulated at the local level.

Chapter 3 While in Chapter 2 we studied relatively nearby galaxies than could be well resolved, in the later Chapters we will study more distant, poorly resolved galaxies.
Resolution loss, which is primarily due to atmospheric seeing, can cause one to observe galaxy metallicity gradients that are much flatter than in reality (Yuan et al. 2013). In order to measure the true metallicity gradients in distant galaxies, it is critical to correct for seeing and other resolution loss effects. This chapter is devoted to developing and testing a method for deriving the intrinsic metallicity profiles from poorly resolved integral-field spectrographic observations. The method we present offers some benefits over existing approaches. These previous methods measure the raw metallicity gradient from the data, and then apply a seeing-dependent correction factor to obtain the true metallicity gradient. In contrast we forward model the effects of seeing and fit our model to the observed emission-line fluxes. By doing so we are not dependent on a using a specific set of emission-lines. And as a result our method is independent of both the galaxy's redshift, and the wavelength coverage of spectrograph used.
We validate our approach using a series of mock observations. The most critical tests are performed using downgraded observations of real galaxies. We find one galaxy where our method fails to derive the correct metallicity profile. This galaxy does not have a well defined metallicity gradient, containing bright low-metallicity clumps. A key model assumption of ours is that there exists a single metallicity gradient that describes the galaxy. But if galaxies do not conform to this our model can fail and we may derive spurious metallicity gradients. We caution that the underlying reason for this failure is not specific to our model and could influence any comparison of metallicity gradients between low and high redshift observations.

Chapter 4 We apply the method developed in Chapter 3 to MUSE observations of 94 intermediate redshift galaxies ($0.08 < z < 0.84$). We identify a range of metallicity gradients in these galaxies. Most galaxies have negative metallicity gradients, but a few galaxies have positive metallicity gradients (with the metallicity in the centre of the galaxy lower than in the outskirts).
It had been suggested by previous studies that the metallicity gradient of a galaxy correlates with its mass and star-formation rate (Stott et al. 2014; Wuyts et al. 2016). However, our results do not support this.
Instead we suggest a dependency between the metallicity gradient and the size of the galaxy. We note that the large galaxies ($r_d > 3$ kpc) typically present negative metallicity gradients, with minimal scatter. Whereas the small galaxies ($r_d < 3$ kpc) span a large range of metallicity gradients (both negative and positive). Galaxies in the Universe today are generally found to have a common negative metallicity gradient. Because of their similarity to low-redshift galaxies, we suggest that the large galaxies in our sample are an emergent population of well-evolved galaxies, where inside-out growth dominates their metallicity profile.

Chapter 5 Using a subsample of the galaxies presented in Chapter 4 we study the relationship between stellar mass, central metallicity and metallicity gradient.
At low redshift ($z \lesssim 0.1$) it has been established that their exists a correlation between a galaxy's mass and its central metallicity (Tremonti et al. 2004; Foster et al. 2012). We observe a similar trend with our intermediate redshift galaxies, but there appears to be more scatter in our data. However, we note that this scatter can be explained by the metallicity gradient. We find at fixed mass the central metallicity is anti-correlated with the metallicity gradient.

This result in consistent with the idea that centrally concentrated inflow and outflow events may lower the central metallicity of a galaxy, flattening/inverting the metallicity gradient. Because inflows and outflows may have different effects on the outer discs of galaxies, we suggest that by studying the mass, central metallicity and metallicity gradients of galaxies all in conjunction one may be able to break the degeneracy between inflows and outflows.

4.1 Outlook

In astronomy today there is a drive towards obtaining larger samples and more complex datasets. With Chapter 2 we demonstrate that one does not need large samples or the latest instrumentation to produce valuable science. That said, in the coming years integral-field spectroscopy will play an ever increase role in the study of galaxy evolution. As a particular example, metallicity studies today primarily discuss the radial metallicity profiles of galaxies entirely ignoring any azimuthal dependence. With integral-field spectroscopy it is now possible to study the latter.

However, in general with bigger data comes greater responsibility. We will need to develop more sophisticated analysis techniques to fully exploit potential of the data. Take for example, the method we present in Chapter 3, which can fail for galaxies with irregular metallicity profiles. The robustness of the method could be improved with a partially or fully non-parametric model. We consider the model presented in Chapter 3 to be a first step for the forward-modelling of metallicity gradients in galaxies, but certainly not the last word.

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