The environmental dependence of the chemical properties of star-forming galaxies

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ABSTRACT

We use a 0.040 < z < 0.085 sample of 37 866 star-forming galaxies from the Fourth Data Release of the Sloan Digital Sky Survey to investigate the dependence of gas-phase chemical properties on stellar mass and environment. The local density, determined from the projected distances to the fourth and fifth nearest neighbours, is used as an environment indicator. Considering environments ranging from voids, i.e. log Σ1 ≲ -0.8, to the periphery of galaxy clusters, i.e. log Σ ≈ 0.8, we find no dependence of the relationship between galaxy stellar mass and gas-phase oxygen abundance, along with its associated scatter, on local galaxy density. However, the star-forming gas in galaxies shows a marginal increase in the chemical enrichment level at a fixed stellar mass in denser environments. Compared with galaxies of similar stellar mass in low-density environments, they are enhanced by a few per cent for massive galaxies to about 20 per cent for galaxies with stellar masses \( \lesssim 10^{9.5} \) M⊙. These results imply that the evolution of star-forming galaxies is driven primarily by their intrinsic properties and is largely independent of their environment over a large range of local galaxy density.

Key words: galaxies: abundances – galaxies: clusters: general – galaxies: evolution – galaxies: fundamental parameters.

1 INTRODUCTION

One of the central problems in astronomy is that of galaxy formation and evolution: when were the various parts of galaxies assembled, when were the stars formed and how did these processes depend on environment? At low redshift the dependence of many galaxy properties on environment is well established. Dense environments contain a larger fraction of red, passive galaxies, while low-density environments contain more blue, star-forming galaxies (e.g. Dressler 1980; Poggianti et al. 1999; Lewis et al. 2002; Gómez et al. 2003). The distributions of colour and Hα equivalent width, and hence inferred star formation histories, are found to be bimodal (Baldry et al. 2004; Balogh et al. 2004a). Surprisingly, the two sequences vary little with environment, except in terms of their relative proportions (Balogh et al. 2004a,b; Baldry et al. 2006). However, some studies find that star-forming galaxies in clusters tend to have a reduced global star formation rate with respect to field galaxies of the same morphological type (Koopmann & Kenney 2004).

The chemical abundances of stars and interstellar gas within galaxies provide a fundamental tool for tracing the evolution of their stellar and metal content. These abundances depend on various physical processes, such as the star formation history, gas outflows and inflows, etc. Variation in the chemical enrichment of galaxies may potentially provide insight into how environment affects galaxy evolution. Measurements of this variation can thus assist in constraining the likely scenarios of galaxy evolution.

The correlation between galaxy metallicity and luminosity is one of the most significant observational results in chemical evolution studies (e.g. Lequeux et al. 1979; Skillman, Kennicutt & Hodge 1989; Zaritsky, Kennicutt & Huchra 1994; Richer & McCall 1995; Melbourne & Salzer 2002; Lee et al. 2006). The analysis of large samples of star-forming galaxies shows that metallicity correlates with luminosity over \( \sim 10 \) mag, with a factor of \( \sim 100 \) increase in metallicity (Baldry et al. 2004). The metallicity relation is tighter versus stellar mass than luminosity (Tremonti et al. 2004).

Spectrophotometric observations of H II regions for a sample of nine Virgo cluster spiral galaxies have shown that H I-deficient objects, near the cluster core, appear to have higher oxygen abundance than field galaxies of comparable luminosity or morphology (Skillman et al. 1996). Oxygen abundances of spirals at the periphery of the cluster with normal H I properties are however indistinguishable from those of field galaxies (Shields, Skillman & Kennicutt 1991; see also Dors & Copetti 2006, for similar results). Due to their lower gravitational potentials, dwarf galaxies ought to be more sensitive to their surroundings and should especially be less able to...
retain their gaseous contents. For a sample of dwarf star-forming galaxies located at different environments, Vilchez (1995) found that galaxies located in low-density regions tend to display higher excitation-sensitive emission-line ratios, with higher emission-line equivalent widths and total luminosities. Dwarf galaxies appear however to follow the same metallicity–luminosity relation, i.e. at a given luminosity, there is no systematic difference in oxygen abundance between cluster and field star-forming dwarf galaxies. Lee, McCall & Richer (2003) have confirmed this result for a sample of dwarf irregulars in the Virgo cluster. A subsample of Virgo star-forming galaxies displays a much lower baryonic gas fraction than their counterparts in the field at comparable oxygen abundances. They argue that the observed gas-poor star-forming galaxies have been stripped of their gaseous content without significant effect on their luminosities and metallicities.

The large dispersion in the chemical properties of field galaxies (see e.g. Zaritsky et al. 1994), and previous small sample sizes in dense regions make it difficult to draw definitive conclusions regarding the effect of environment on the chemical properties of galaxies. The large data sets provided by the Sloan Digital Sky Survey (SDSS) now allow the environmental effects on galaxy properties to be followed statistically over the full range of environments, from the sparse field to dense cluster cores, at least for bright galaxies. Additionally, the homogeneity of the SDSS sample enables us to sample the entire range of galactic environments, in a uniform manner. We can now, therefore, expand the study of galaxy chemical properties from the usual cluster versus field comparison to general environment, in this case characterized by local density, irrespective of actual cluster or group membership. This will help strongly in constraining the physical processes responsible for determining galaxy properties. In this paper, we analyse the variation in oxygen abundance of the interstellar star-forming gas for a large sample of local galaxies as a function of their stellar mass and environment, in order to investigate environmental effects on the chemical content of galaxies, and how it depends on galaxy mass.

The paper is organized as follows. In Section 2 we describe the sample selection. In Section 3, we investigate the environmental dependence of the stellar mass versus gas-phase oxygen abundance relationship. The implications of our results and our conclusions are summarized in Section 4. The cosmological model with Ωm = 0.3, ΩΛ = 0.7 has been adopted throughout the paper.

2 DATA AND SAMPLE SELECTION

The SDSS is a project with a dedicated 2.5-m telescope designed to image 10° deg−2 and take spectra of 106 objects (York et al. 2000). The imaging covers five broad-bands, ugriz, with effective wavelengths from 350 to 900 nm. The spectra are obtained using a fibre-fed spectrograph with 3 arcsec apertures. This aperture size corresponds to 1800. The majority of spectra are taken for galaxies with r < 17.77, called the main galaxy sample (MGS) (Strauss et al. 2002). The sample analysed here was selected from SDSS Data Release Four (DR4) (Adelman-McCarthy et al. 2006). The initial sample consisted of 151 168 MGS galaxies in the redshift range 0.010–0.085. The sample is volume limited for galaxies brighter than Mr = −20, which is the density defining population (DDP). For magnitudes fainter than this limit, the sample is magnitude limited. Data on these galaxies were taken from the standard PHOTO and spectroscopic data reduction pipelines (Stoughton et al. 2002), along with additional measurements from the MPA Garching DR4 data (Kauffmann et al. 2003a; Brinchmann et al. 2004; Tremonti et al. 2004) and environmental measurements (Baldry et al. 2006).

Environmental density measurements were determined using an Nth nearest neighbour technique. Galaxies more luminous than Mr < −20 were used for the DDP: with an average space density of 0.005 Mpc−3. The environmental density for each galaxy is then given by

$$\log \Sigma = \frac{1}{2} \log \left( \frac{4}{\pi d_4^2} \right) + \frac{1}{2} \log \left( \frac{5}{\pi d_5^2} \right) \, ,$$

where $d_4$ and $d_5$ are the projected distances to the fourth and fifth nearest DDP neighbours within 1000 km s−1. For typical galaxies, Σ ranges from 0.05 Mpc−2, typical of void-like regions, to 20 Mpc−2, typical of the centres of galaxy clusters. A best estimate Σ, and minimum and maximum values, were determined taking account of edge effects and galaxies that had not been observed spectroscopically. For example, Σmax was determined by using the smaller of (i) the distance to the nearest edge and (ii) the distance to the fourth/fifth nearest photometrically confirmed neighbours. See Baldry et al. (2006) for details.

From this sample, only galaxies for which emission lines are well detected were retained. We require galaxies included in our star-forming sample to have lines of [O II]λ3727,[O III]λ5007, Hβ, Hα and [N II]λ6584 detected at greater than 5σ, reducing the sample to 68 603. Galaxies with $z < 0.03$ are excluded from the sample due to the blue wavelength cut-off of the spectrograph. We have distinguished star-forming galaxies from non-thermal sources, such as active galactic nuclei (AGN), using the classical diagnostic ratios of two pairs of relatively strong emission lines, i.e., [O II]λ5007/Hβ versus [N II]λ6584/Hα diagrams (Baldwin, Phillips & Terlevich 1981; Veilleux & Osterbrock 1987). We have used the empirical demarcation line, separating star-forming galaxies from AGN, provided by Kauffmann et al. (2003b). The selection of star-forming galaxies reduced the sample to 51 934 galaxies. In order to avoid edge effects, galaxies with (log Σmax − log Σ) > 0.4 were excluded from the analysis. This reduced the sample to 45 107 galaxies.

For fibre-fed spectroscopy, the fraction of the light of a galaxy captured within the fibre will depend on its redshift, intrinsic size and surface brightness profile, as well as the size of the fibre and seeing during the observation. Kewley, Jansen & Geller (2005) have shown that using the spectra of the inner parts of galaxies could have a substantial systematic effect on the estimate of their global properties. To reduce systematic and random errors from aperture effects, they recommended selecting SDSS galaxies with $z > 0.04$. Doing so reduces the size of the sample to 37 866 galaxies.

Gas-phase oxygen abundances are taken from the catalogues of derived physical properties for DR4 galaxies released by the MPA Garching group (Tremonti et al. 2004). Briefly, gas-phase oxygen abundances are estimated based on simultaneous fits of all the most prominent emission-line fluxes ([O II]λ3727, Hβ, [O III]λ5007, Hα, [N II]λ6584, [S II]λ6717, 6731) with a model designed for the interpretation of integrated galaxy spectra based on a combination of population synthesis and photoionization codes (Charlot & Longhetti 2001). The likelihood distribution of the metallicity of each galaxy in the sample is calculated, based on comparisons with a large library of models corresponding to different assumptions about the effective interstellar star-forming gas parameters. The median of this distribution is adopted as the best estimate of the galaxy metallicity. The estimated metallicities show good agreement
with those estimated using the so-called strong emission-line method. The width of the likelihood distribution provides a measure of the error. The median 1σ error for our final sample of star-forming galaxies is ~0.04 dex.

The computation of stellar masses by the MPA Garching group is obtained by fitting a grid of population synthesis models, including bursts, to the spectral features D4000 and Hδ absorption. The predicted colours are then compared with broad-band photometry to estimate dust attenuation. Stellar mass-to-light ratios are determined and applied to the Petrosian r-band magnitude. The nominal 1σ random errors are typically ~0.1 dex. For details see Kauffmann et al. (2003a). Assuming most galaxies have stellar mass estimates with relative uncertainties less than 0.2 dex, these have little impact on our results.

Selecting only galaxies with high signal-to-noise ratio (S/N) emission lines could potentially bias the distribution of galaxy properties in the selected final sample in such a way to affect the intrinsic correlations between galaxy properties that we aim to investigate. Therefore it is important to assess to what extent the final sample of star-forming galaxies covers similar regions in the parameter space as star-forming galaxies in original sample. To ensure that the final sample of star-forming galaxies is representative of the parent sample, we compare the distribution of galaxy properties in the final sample with those of a more lenient selection. These were selected from the initial MGS sample, as those with S/N larger than 3 in emission lines needed to classify the ionizing source, i.e. [O iii]λ5007, Hβ, Hα and [N ii]λ6584.

Fig. 1 shows the distributions of stellar mass, star formation rate, abundance-sensitive diagnostic ratio ([O ii]λ4959, λ5007+[O ii]λ3727)/Hβ, and excitation-sensitive diagnostic ratio [O iii]λ4959, λ5007/[O ii]λ3727 for both the final and the parent samples of star-forming galaxies. The distributions of the properties of the star-forming galaxies in the parent sample are shown in the upper panels, and those of the final sample are shown in the lower panels. Solid lines show the distribution of the properties of galaxies situated in rarefied field regions, i.e. log Σ < −0.8, and dotted lines show the distribution of the properties of those situated in dense region, i.e. log Σ > 0.8. The figure shows clearly that the final sample has galaxy parameter distributions similar to those of the parent star-forming galaxy sample. Most importantly, the differences with respect to the environment are the same for the two different selections. Observed abundance- and excitation-sensitive diagnostic ratios are distributed similarly in both samples. However, the redshift cut, imposed to minimize the effects of the aperture bias, appears to slightly affect the extent of the low-end tails of stellar mass and star formation rate distributions, i.e. the low ends of both distributions for the final sample are less extended than for the parent star-forming galaxy sample. The cut on redshift excludes low stellar mass galaxies, as those galaxies tend to be at low redshift end. Those galaxies represent however a small fraction of the sample. The high ends of the star formation rate and the stellar mass distributions are however unaffected by the redshift cut. The similar distributions of both star-forming galaxy samples suggest that our final sample is a fair representation of the parent sample in terms of its stellar mass, star formation activity, interstellar gas-phase properties. The correlations we aim to investigate are therefore expected to not be severely biased by the selection procedure of the final sample of star-forming galaxies.

The distributions of global properties for our final sample, i.e. r-band absolute magnitudes, specific star formation rate, local galaxy density and the concentration index, defined as the ratio of the radii enclosing 50 per cent (R50) and 90 per cent (R90) of the Petrosian r-band galaxy light, are shown in Fig. 2.

Fig. 3 shows the relationship between the integrated (u − r) colour and the stellar mass for six local galaxy density bins ranging from log Σ < −0.8 to log Σ > 0.8 (see below). The distribution of the final sample of galaxies is shown as solid contours and points. The full parent sample of galaxies in the redshift range 0.010–0.085 is shown as the dash–dotted contours. The bimodal nature of the colour–stellar mass relation for the complete sample is clear: red galaxies dominate in dense regions and at higher masses, while the dominance of blue galaxies is clear at lower masses and for lower local densities (see Baldry et al. 2006, for more details). The selected galaxies are distributed along the blue sequence. This is no
Figure 2. Distribution of general properties of our sample of star-forming galaxies. The upper panels show the absolute $r$-band magnitude and specific star formation rate. The lower panels show the distributions of local galaxy density and (inverse) concentration index.

surprise, as star-forming galaxies with well detected emission lines tend to have blue colours.

3 RESULTS

The selected sample of star-forming galaxies was divided into bins of local galaxy density and stellar mass in order to determine the variation of gas-phase oxygen abundances as a function of these quantities. Fig. 4 shows the gas-phase oxygen abundance distribution of galaxies in bins of galaxy local density and stellar mass. The median local galaxy density in the selected sample is $\Sigma \sim 0.4 \text{ Mpc}^{-2}$; thus, the lowest local galaxy density bin, with a median density of $\Sigma \sim 0.1 \text{ Mpc}^{-2}$ is underdense by a factor of $\sim 4$, while the densest bin with a median density of $\Sigma \sim 10 \text{ Mpc}^{-2}$, corresponds to the typical galaxy density found in the inner regions of galaxy clusters.

Our selection function preferentially selects morphologically late-type galaxies. However, because the strongest effect with environment is the early-/late-type galaxy fraction; we split the sample into nominally early- and late-type galaxies. The (inverse) concentration index is used as a proxy for galaxy morphology: with $R_{50}/R_{90} \sim 0.4$ marking the boundary between early- and late-types (Shimasaku et al. 2001; Strateva et al. 2001). Baldry et al. (2006) have found that a concentration index around $\sim 0.4$ is a natural dividing line between red and blue galaxy populations for all stellar masses. Driver et al. (2006) also show that galaxies naturally divide into two populations in the concentration–colour plane, which can be associated with late- and early-types. Solid (dotted) line histograms in Fig. 4 represent gas-phase oxygen abundance distributions for galaxies with concentration index lower (higher) than 0.4. The distributions of gas-phase oxygen abundances of star-forming galaxies with concentration indices larger (late-type population) and lower (early-type population) than the dividing value are indistinguishable for all environments.

In all local galaxy density bins, the median of the gas-phase oxygen abundance distribution increases with increasing stellar mass, i.e. the so-called stellar mass–metallicity relation is present in all environments. The dispersion of the gas-phase oxygen abundance
Figure 4. Distributions of galaxy gas-phase oxygen abundance for the indicated range of stellar mass (right-hand axis) and the range of local galaxy density in units of Mpc$^{-2}$ (top axis). The solid lines represent galaxies with concentration indices lower than 0.4 (nominally early-types), while the dotted lines represent those larger than 0.4 (nominally late-types). The number of galaxies in the bin, the mean of their redshift distribution and average metallicity are given in each panel.

distribution increases at lower stellar mass, where the fraction of star-forming galaxies increases (e.g. Balogh et al. 2004a), but appears to be insensitive to environment.

Most remarkable is the mass dependence of the environmental effect on galaxy gas-phase oxygen abundance. For massive galaxies, i.e. stellar masses larger than $\sim 10^{10.5} \, M_\odot$, the oxygen abundance distribution median does not show any significant dependence on the environment. However, for low-mass galaxies ($\sim 10^{9.5} \, M_\odot$), the abundance distribution median increases by 0.06–0.08 dex from low-density environments, i.e. log $\Sigma_{1} < -0.8$, to highly dense regions, i.e. log $\Sigma_{1} \approx 0.8$.

To determine the variation of the stellar mass versus gas-phase oxygen abundance relation as a function of the environment, we have divided the star-forming galaxy sample into local galaxy density bins. Fig. 5 shows the relationship for six local density bins ranging from log $\Sigma < -0.8$ to log $\Sigma > 0.8$. In each panel, the large filled circles show the median gas-phase oxygen abundance in bins of 0.15 dex in stellar mass containing more than 50 galaxies, and the thick line shows a polynomial fit to these points. The thin solid line shows the fit to the stellar mass versus oxygen abundance for galaxies in low-density regions, i.e. log $\Sigma < -0.8$ (only visible in the higher density bins). The correlation is relatively steep from $10^{9.5}$ to $10^{10.5} \, M_\odot$, but flattens for more massive galaxies (as discussed by Tremonti et al. 2004).

Most striking of all is the similarity of the correlation between stellar mass and gas-phase oxygen abundance over a large range of local galaxy densities, from log $\Sigma < -0.8$, typical of void-like environments, to log $\Sigma \approx 0.8$, typical of the outer regions of galaxy clusters. This is in agreement with previous findings, that star-forming galaxies in the periphery of the Virgo cluster exhibit similar oxygen abundances to those of field galaxies with similar luminosities (Skillman et al. 1996; Pilyugin et al. 2002). The spread of oxygen abundances about the median is identical at all environments across the entire galaxy stellar mass range. The bottom right-hand panel of Fig. 5 shows, however, that stellar mass versus oxygen abundance relationship at denser environments, i.e. log $\Sigma > 0.8$ typical of the inner parts of galaxy clusters, is shallower than the relationship for galaxies in less dense regions. Gas-phase oxygen abundances show a mass-dependent shift to higher values that is larger for low stellar mass galaxies. This seems to disagree with the results of Skillman...
et al. (1996) who found that the interstellar star-forming gas of bright galaxies near the core of the Virgo galaxy cluster appear to be overabundant by 0.2–0.3 dex in comparison with field galaxies with similar luminosities. Pilyugin et al. (2002) have confirmed the higher abundances for the same Virgo galaxies studied by Skillman et al., although they have found counterparts for both the periphery and core cluster objects among field star-forming galaxies. They have concluded that if there is a difference in the abundance properties of the Virgo and field bright spirals, this difference appears to be small, in agreement with our results.

Fig. 6 shows the variation of gas-phase oxygen abundance as a function of local galaxy density for different stellar mass bins. Over a factor ~100 in local galaxy density the median gas-phase oxygen abundance changes by only 0.02–0.08 dex, depending on stellar mass, being greater at the low stellar mass end. These trends are weak, relative to the stellar mass dependence: the median gas-phase oxygen abundance is ~0.7 dex higher in the massive galaxies, compared with the low-mass galaxies in the same environment.

Fig. 7 shows the relationship between the specific star formation rate and the stellar mass for star-forming galaxies in dense environments, log $\Sigma > 0.8$. We use the star formation rates corrected to total computed by Brinchmann et al. (2004). Note that this sample only includes galaxies which are actively star forming, due to our requirement on significant emission-line detections. However, it still meaningful to consider star-forming galaxies alone in this diagram, due to the bimodality in specific star formation rates, e.g. as seen by Balogh et al. (2004a) considering the H$\alpha$ equivalent width distribution. As in Fig. 5, the thick line shows a polynomial fit to the variation of the specific star formation rate median, shown as large field circles, as a function of the stellar mass. The thin solid line shows the fit to the same correlation for galaxies situated in low-density regions, i.e. log $\Sigma < -0.8$.

Similar to the stellar mass versus oxygen abundance relation, the correlation between the specific star formation rate and the stellar mass of star-forming galaxies shows very little dependence on local galaxy density from void-like environments, i.e. log $\Sigma < -0.8$, to the periphery of galaxy clusters, i.e. log $\Sigma \approx 0.8$. For star-forming galaxies in dense regions, i.e. log $\Sigma > 0.8$, the median of the specific star formation rate distribution is, however, ~0.03 dex higher than for galaxies with similar stellar masses in less dense regions.

4 SUMMARY AND DISCUSSIONS

Using a complete sample of 151 168 galaxies in the redshift range of 0.01 < $z$ < 0.085 from the SDSS DR4, we draw a sample of 37 866 star-forming galaxies in the redshift range of 0.04 < $z$ < 0.085 to examine how oxygen abundances of the interstellar star-forming gas relate to environment. We use the projected distance to the fourth and fifth nearest neighbours as an indicator of local galaxy density. The stellar mass versus gas-phase oxygen abundance relationship appears to be environment-free over a large range of local galaxy densities. For galaxies located in environments with local galaxy densities typical of the inner regions of galaxy clusters, the interstellar star-forming gas is found to be slightly overabundant compared to what is found for their counterparts of similar stellar masses in less dense environments. This change in oxygen abundance increases as galaxy stellar mass decreases, ranging from...
Figure 6. Gas-phase oxygen abundance versus projected local galaxy density for different stellar mass bins. Large filled circles show the median in bins of 0.15 dex in projected local galaxy density.

Figure 7. Specific star formation rate versus stellar mass for galaxies in dense regions, i.e. log Σ > 0.8. The large filled points represent the median in bins of 0.1 dex in mass. The thick line shows a polynomial fit to the data, and the thin line shows the fit to the same relation for galaxies with log Σ < −0.8.

∼0.2 dex for galaxies with stellar mass larger than ∼10^{10} M_☉ to ∼0.08 dex for galaxies with stellar mass around ∼10^{9} M_☉.

Over that last few years, observational evidence has been accumulating that the dominant evolution in the galaxy population properties as a function of environment is the change of the ratio between star-forming/blue galaxies and passive/red galaxies (e.g. Dressler 1980; Baldry et al. 2006, and reference therein). The environmental dependence of different galaxy properties, i.e. colour, concentration index and colour gradient are found to be almost entirely due to the dependences of galaxy morphology and luminosity on the environment: when morphology and luminosity are fixed, galaxy physical properties are nearly independent of local galaxy density (Park et al. 2007). The scaling relations for both passive and star-forming galaxies are virtually unaffected by environment. Studies of the fundamental plane have shown that the properties of early-type galaxies are nearly independent of environment (e.g. Dressler et al. 1987; Bernardi et al. 2003). The scaling relations for star-forming galaxies are virtually unchanged with environment, whilst over the same density range the fraction of star-forming galaxies is changing strongly (e.g. Balogh et al. 2004a; Blanton et al. 2005; Baldry et al. 2006).

Our finding that oxygen abundances of galaxies with a given stellar mass depend weakly on environment is consistent with (i) the weak dependence on environment of the mean colour, at a given luminosity, of blue galaxies that are still actively growing and evolving, compared with the dependence on luminosity, the strongest effect also being seen for faint galaxies (Balogh et al. 2004b) and (ii) the lack of any environmental effect on the distribution of the emission-line equivalent width for star-forming galaxies (Balogh et al. 2004a).

The weak dependence of the star-forming gas oxygen abundance shown here is a further suggestion that the primary physical driver(s) of galaxy evolution must depend primarily on galaxy intrinsic properties rather than on their environment. In addition, whatever mechanism is responsible for the increasing fraction of passive galaxies in dense environments, it must truncate their star formation on a short time-scale to avoid affecting the relations of oxygen abundance and specific star formation versus stellar mass for actively star-forming galaxies. Yet Kauffmann et al. (2004) have argued, based on the absence of dependence on environment of the correlations between different spectral indicators that probe star formation history on different time-scales (SFR/M_*, D4000, Hδ), that the decrease in star formation activity in dense environments occurs over long (≥1 Gyr) time-scales. It is not clear however how slow quenching could affect the chemical properties of galaxies, and for which kind of star formation histories galaxies would move along the observed relations in different environments. Self-consistent modelling is clearly needed in order to set tight constraints on quenching time-scales from observed chemical and spectrophotometric...
properties of galaxies. This is obviously well beyond the scope of this paper, and we will leave it for future investigations.

The modest change of oxygen abundances of star-forming galaxies in regions with local galaxy densities typical of the inner regions of galaxy clusters indicates however that the chemical evolution of galaxies is moderately modulated by the environment. Furthermore, the mechanism responsible for this change must be more efficient in low stellar mass galaxies, as the change of oxygen abundances is larger for those galaxies. The relationship between stellar mass and oxygen abundance can be understood either as a sequence in astration, i.e. more massive galaxies are able to convert a larger fraction of their gas into stars than low-mass counterparts, or as a depletion sequence, i.e. the efficiency of galaxies to retain their gas increases with galaxy mass. Based on the correlation between effective yield and baryonic mass for local star-forming galaxies, Tremonti et al. (2004) have argued that the most straightforward interpretation of the correlation is the selective loss of metals from galaxies with shallow potential wells via galactic winds. This suggests that the change of 0.02–0.08 dex in the mean gas-phase oxygen abundance of star-forming galaxies as a function of environment can be explained by a reduced effectiveness of galactic winds in removing metals from the potential wells of low-mass haloes in dense regions. There is consequently more gas left to be turned into stars. Massive galaxies can however retain all their gas whether they are in the field or in a cluster. In this scenario, therefore, the efficiency of star formation within low-mass haloes is higher in the presence of a confining intergalactic medium, because supernovae are less efficient at removing gas from a galaxy if there is hot material surrounding the galaxy.

An alternative explanation of the observed mass-dependent change in oxygen abundances of galaxies as a function of environment might be that low stellar mass galaxies have assembled their stellar contents at a faster rate in denser regions. Whatever triggers star formation in galaxy clusters, it causes it to happen rapidly, hence increasing the efficiency of recycling during star formation. Environment-driven processes, i.e. tidal interactions, mergers, could enhance the star formation activity in low-mass galaxies in cluster environment. The observed systematic difference of specific star formation rate between field and cluster galaxies may be the signature of such an effect.

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