The mass–metallicity relation in galaxy clusters: the relative importance of cluster membership versus local environment

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ABSTRACT
Using a large (14,857), homogenously selected sample of cluster galaxies identified in the Sloan Digital Sky Survey Data Release 4, we investigate the impact of cluster membership and local density on the stellar mass–gas phase metallicity relation (MZR). We show that stellar metallicities are not suitable for this work, being relatively insensitive to subtle changes in the MZR. Accurate nebular abundances can be obtained for 1318 cluster galaxies in our sample and we show that these galaxies are drawn from clusters that are fully representative of the parent sample in terms of mass, size, velocity dispersion and richness. By comparing the MZR of the cluster galaxies with a sample of control galaxies matched in mass, redshift, fibre covering fraction and rest-frame $g-r$ colour cluster galaxies are found to have, on average, higher metallicities by up to 0.04 dex. The magnitude of this offset does not depend strongly on galactic half-light radius or cluster properties such as velocity dispersion or cluster mass. The effect of local density on the MZR is investigated, using the presence of a near neighbour and both two- and three-dimensional density estimators. For all three metrics, it is found that the cluster galaxies in locally rich environments have higher median metallicities by up to $\sim$0.05 dex than those in locally poor environments (or without a near neighbour). Control (non-cluster) galaxies at locally high densities exhibit similar metal enhancements. Taken together, these results show that galaxies in clusters are, on average, slightly more metal rich than the field, but that this effect is driven by local overdensity and not simply cluster membership.

Key words: galaxies: abundances – galaxies: clusters: general – galaxies: ISM.

1 INTRODUCTION
Is it nature or nurture that governs the evolution of a galaxy? Understanding the relative importance of the intrinsic physical properties of a galaxy (such as its mass, gas fraction and morphological characteristics) versus environmental effects has been an on-going endeavour in extragalactic astronomy. The presence of apparently fundamental scaling relations, such as the Tully–Fisher relation, the correlation of black hole and spheroid mass and the Fundamental Plane (e.g. Faber & Jackson 1976; Tully & Fisher 1977; Ferrarese & Merritt 2000), indicates that internal processes that respond to intrinsic galaxy properties may play the principal role in galaxy evolution. However, galaxies clearly also respond to environmental factors. Galaxy interactions and mergers can cause gas inflows, morphological transformations, trigger star formation and ultimately lead to activity in the galactic nucleus (Barton, Geller & Kenyon 2000; Lambas et al. 2003; Nikolic, Cullen & Alexander 2004; Alonso et al. 2007; Woods & Geller 2007; Ellison et al. 2008a). Larger scale environment also plays a role in modulating star formation rates (SFRs), which are systematically lower in cluster galaxies, particularly in their cores, possibly as a result of an earlier starburst, or a more gradual process of gas exhaustion (e.g. Balogh et al. 1997, 1998, 1999; Poggianti et al. 1999; Koopmann & Kenney 2004). However, it appears that local density, on scales $<1\,\text{Mpc}$, may be more important than simple cluster membership in suppressing star formation (e.g. Lewis et al. 2002; Gomez et al. 2003; Kauffmann et al. 2004; Blanton et al. 2007; Park, Gott & Choi 2008; Welikala et al. 2008). The local density of galaxies also modulates the average stellar mass, nuclear activity

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and dust content (Kauffmann et al. 2004). Star formation, it seems, responds to both intrinsic and external factors.

The star formation history of a galaxy is thus a record of the processes that have influenced its evolution. Star formation eventually leads to the production of metals, and a correlation between a galaxy’s stellar mass and its metallicity has been observed out to at least \( z \sim 3 \) (Tremonti et al. 2004; Savaglio et al. 2005; Erb et al. 2006; Hayashi et al. 2009; Maiolino et al. 2008). Given the contributions of both intrinsic (‘nature’) and environmental (‘nurture’) processes to the rate of star formation, the scatter in the stellar mass–metallicity relation is surprisingly small, only 0.1 dex at \( z \sim 0.1 \) (Tremonti et al. 2004). There are several interpretations for the small observed scatter. For example, it may be that the mass–metallicity relation is dominated by local processes linked to stellar mass and that metallicity is relatively insensitive to environmental effects. Alternatively, environmental processes that trigger short-lived bursts of star formation may cause a significant, but transient change in a galaxy’s metallicity before it returns to an equilibrium metallicity (Finlator & Davé 2008).

A number of studies have recently revealed some clues to the relative importance of intrinsic and environmental effects on the mass–metallicity relation. First, it has been shown that the mass–metallicity relation is insensitive to galaxy morphology, as quantified by its concentration or bulge fraction (Tremonti et al. 2004; Ellison et al. 2008b). Conversely, galaxies with small half-light radii \( r_h \) or low specific star formation rates (SSFR; SFR per unit mass) at a given stellar mass have elevated metallicities (Ellison et al. 2008b). Half-light radius and SSFR account for a spread of up to about 0.2 dex in the stellar mass–metallicity relation. Environment seems to play a more modest role. Mouchine, Baldry & Bamford (2007) and Cooper et al. (2008) both studied star-forming galaxies in the Sloan Digital Sky Survey (SDSS) as a function of local density. The gas-phase metallicity for galaxies (at a given stellar mass) in the richest environments is only \( \sim 0.05 \) dex higher than those in the poorest environments and contributes to \( \sim 15 \) per cent of the total scatter in the mass–metallicity relation. Building on the work of Sheth et al. (2006), who found that higher SFRs in dense environments at \( z \sim 3 \) lead to enhanced chemical enrichment, Panter et al. (2008) find that the mass-weighted average metallicity of \( z > 0.5 \) galaxies depends on the number of cluster members over smoothing scales of a few degrees. Both Sheth et al. (2006) and Panter et al. (2008) find that at \( z < 0.5 \) there is little correlation between metallicity and environment.

A more significant environmental effect is observed at much smaller scales e.g. for galaxies either involved in close interactions, or those that may have recently experienced a merger. Kewley, Geller & Barton (2006) and Ellison et al. (2008a) both found that galaxies in close pairs are more metal poor by approximately 0.1 dex at a given luminosity, compared with galaxies with no near companion. Ellison et al. (2008a) also found that, at a given stellar mass, the close pairs have lower metallicities by 0.05 dex, indicating that the offset in the luminosity–metallicity relation is due to both suppressed metallicity and increased luminosity. Selecting galaxies that showed signs of recent, intense star formation activity, possibly due to a merger, Hoopes et al. (2007) and Rupke, Veilleux & Baker (2008) also found depressed metallicities by up to 0.3 dex. The interpretation of these results is that galaxies involved in interactions experience an inflow of metal-poor gas to their centres which triggers a burst of star formation which in turn enriches the interstellar medium (ISM). Hence, galaxies observed early in this sequence have low metallicities due to metal-poor gas inflow, but once the interaction-induced star formation is complete, the newly synthesized metals enhance the ISM metallicity. However, several questions remain unanswered. For example, what is the time-scale for metallicity modulation in interactions/rich environments? Do galaxies in rich environments remain metal enhanced, or do they return to an equilibrium metallicity for their mass, as suggested by some models (Finlator & Davé 2008)? On what scale can local environment alter the position of a galaxy in mass–metallicity space? These questions can be addressed by studying the chemical abundances of galaxies in clusters. Although the cores of clusters represent some of the richest and most overdense environments in the Universe, their outskirts can be relatively of low density. Clusters also host galaxies in a range of evolutionary phases – starbursts, mergers and passively evolving gas-exhausted galaxies can all be found in galaxy clusters. Clusters therefore present the possibility to disentangle the various processes affecting a galaxy’s metallicity. However, there have been relatively few studies of the dependence of galaxy metallicity in clusters, and extant results paint a confusing picture.

Skillman et al. (1996) found that H I deficient galaxies in the centre of the Virgo cluster exhibit metallicity enhancements relative to galaxies at the cluster periphery and field spirals of similar luminosities by 0.3 to 0.5 dex. The metallicity enhancement in these late-type Virgo cluster galaxies has been confirmed by Pilyugin et al. (2002) and Dors & Copetti (2006). Skillman et al. (1996) concluded that local dynamical processes are more important than simple cluster membership in determining the metallicity of a galaxy. However, the Virgo cluster sample consists of only nine spiral galaxies, of which three are H I poor. The field spiral galaxy sample with which they make their comparison (Zaritsky, Kennicutt & Huchra 1994) had previously been used to demonstrate that metallicity depends not only on luminosity, but also on Hubble type and maximum circular velocity. Skillman et al. (1996) indeed conclude that “the dispersion in properties of field galaxies and the small size of the Virgo sample make it difficult to draw definitive conclusions about any systematic differences between the field and Virgo spirals”. At higher redshifts, Mouchine et al. (2006) studied 17 massive star-forming cluster galaxies between \( 0.3 < z < 0.6 \) and found that their metallicities were consistent with the field.

There are also conflicting results for lower mass galaxies. Vilchez (1995) and Lee, McCall & Richer (2003) both found that local cluster dwarfs have metallicities (at a given luminosity) consistent with the field. However, in a more recent study, Lee, Bell & Somerville (2008) found that stellar metallicities tend to be lower at a given baryonic mass for cluster dwarfs than their field sample.

The main limitation of these studies has been a statistical one, with insufficient numbers of galaxies available to fully dissect possible trends from the many interconnected parameters of galaxy evolution. In this paper, we tackle the question of environmental metallicity dependence by using the statistical power of the SDSS. Our method fundamentally differs from that of Mouchine et al. (2007) and Cooper et al. (2008), who look for offsets in the mass–metallicity relation as a function of local density. The approach taken here is to assemble a sample of known cluster galaxies and to compare them to a control sample that is matched in basic physical properties. This distinction is important in assessing whether it is simply the local density of galaxies that influences chemical enrichment, or whether cluster membership is important. For example, Poggianti et al. (2008) find that even though the fraction of post-starburst galaxies is nearly independent of local density, post-starbursts preferentially reside in massive clusters. This was interpreted as evidence that the intracluster medium plays an important role in shutting down star formation in these galaxies.
The paper is organized as follows. Sections 2 through 4 describe the pre-analysis steps of sample selection, metallicity diagnostic choice and the characterization of galaxy cluster properties. Specifically, in Section 2 the selection of the cluster galaxies from the SDSS Data Release 4 (DR4) is described. Both stellar and nebular metallicities are available for this sample and in Section 3 we describe the advantages and disadvantages of these two diagnostics and argue that the gas-phase abundances are best suited to this study. Section 4 describes the compilation of the control sample to which the cluster galaxy mass–metallicity relation will be compared. The main science results of this paper are presented in Sections 5 (dependence of the mass–metallicity relation on cluster membership) and 6 (dependence of the mass–metallicity relation on local environment).

2 SELECTION OF THE MASS–METALLICITY SAMPLE

The cluster galaxies in our sample have been identified using the C4 algorithm which selects cluster members based on a seven-parameter assessment of both position and colour. The algorithm was applied to the SDSS Data Release 2 (DR2) by Miller et al. (2005) and subsequently extended to later data releases (e.g. von der Linden et al. 2007). Miller et al. (2005) estimate that the DR2 C4 cluster sample is approximately 90 per cent complete and 95 per cent pure. Von der Linden et al. (2007) critically re-assessed the C4 catalogue, improving the cluster velocity dispersions and redshifts. Following these refinements, von der Linden et al. (2007) constructed a sample of 625 clusters from the SDSS DR4 for which the brightest cluster galaxy (BCG; $z ≤ 0.1$) can be confidently identified. These 625 clusters, containing a total of 18 100 galaxies, represent the parent sample from which we compile our list of cluster galaxies. In order to be considered in our final cluster sample, we further require the following.

(i) The extinction-corrected Petrosian r-band magnitude is in the range $14.5 < r < 17.77$.
(ii) Redshifts are available and that the SDSS redshift quality control flag $z_{\text{flags}} > 0.7$.
(iii) Objects are unique and have a SciencePrimary flag $= 1$ (to remove spectroscopic duplicates).
(iv) Galaxies are assigned to a unique cluster. In the original C4 sample of 18 100, 1179 galaxies have been assigned to more than one cluster.
(v) Galaxy stellar masses are available in the Kauffmann et al. (2003) catalogue.
(vi) The fibre covering fraction (CF) is at least 20 per cent in the g band in order to avoid aperture effects.
(vii) Both g- and r-band magnitudes are available. These are converted to the rest frame using k-corrections from Blanton & Roweis (2007).

These cuts yield a sample of 14 857 galaxies in what we shall refer to as the refined C4-DR4 catalogue. Only a subset of these galaxies has some reliable measurement of metallicity. In the following section we describe our selection of those galaxies and the technique that is used to quantify the galaxy metallicity.

3 STELLAR VERSUS NEBULAR METALLICITIES

Almost all extant work on the global stellar mass–metallicity relation of galaxies uses nebular metallicities derived from strong emission lines (e.g. Tremonti et al. 2004; Ellison et al. 2008a,b; Michel-Dansac et al. 2008; Peeples, Pogge & Stanek 2008), including previous work on the mass–metallicity relation as a function of environment (Mouhcine et al. 2007; Cooper et al. 2008). Although there is a large scatter for individual galaxies, stellar metallicities statistically trace nebular metallicities, leading to a similar relation between stellar mass and stellar metallicity (Gallazzi et al. 2005). A number of authors have noted the tendency for stellar metallicities to be offset to lower values than nebular metallicities (e.g. Cid Fernandes et al. 2005; Gallazzi et al. 2005; Asari et al. 2007; Halliday et al. 2008; Panter et al. 2008). This is usually attributed to the fact that stellar metallicities trace the aggregate past of metal enrichment, whereas nebular metallicities contain a significant contribution of metals from the most recent star formation episodes. A further factor may be the calibration of nebular metallicities. Kewley & Ellison (2008) have shown that, depending on the choice of strong line nebular abundance diagnostic, the metallicity at a given stellar mass can vary by up to 0.7 dex (a factor of 5). In this section we consider whether stellar or nebular metallicities are best suited to our investigation of the cluster mass–metallicity relation. Our choice is driven by requiring both sensitivity to environmental effects and statistical leverage (sample size).

In the first instance, it may appear that stellar metallicities are the better choice for investigating galaxies in clusters, due to the high fraction of passively evolving galaxies therein. Gallazzi et al. (2005) showed that despite a large scatter between the nebular and stellar metallicities of individual galaxies, an overall relation between stellar mass and stellar metallicity does exist, albeit with larger scatter than the stellar mass–nebular metallicity relation of Tremonti et al. (2004). Since the offset in the mass–metallicity relation due to
environment may be comparable to the scatter (e.g. Cooper et al. 2008; Ellison et al. 2008a,b) we begin by assessing whether known trends in the stellar mass–metallicity relation can be recovered when stellar metallicity is used instead of nebular metallicity. In the following tests we use the nebular metallicities of SDSS DR4 galaxies determined from the Kewley & Dopita (2002) ‘recommended’ calibration and stellar metallicity from Gallazzi et al. (2005). In order to be considered in our metallicity analysis, we require the following additional criteria.

(i) A median spectral signal-to-noise ratio (S/N) of 20 pixel\(^{-1}\) for stellar abundance determinations (Gallazzi et al. 2005). For the calculation of nebular abundances, we require that the S/N in the emission lines of O\(\,\)\(\ii\)\(\lambda\)\(\lambda\)3726, 9, H\(\beta\), O\(\,\)\(\iii\)\(\lambda\)5007, H\(\alpha\), N\(\,\)\(\ii\)\(\lambda\)6584 and S\(\,\)\(\ii\)\(\lambda\)\(\lambda\)6717, 31 is greater than 5.
(ii) Classification as an H\(\,\)\(\ii\) region dominated galaxy for nebular abundance determination. We use the Kewley et al. (2001) line ratio classification scheme to determine which galaxies have an active galactic nucleus (AGN) component.

Ellison et al. (2008b) showed that the stellar mass–nebular metallicity relation is separated into clear trends of half-light radius and SSFR. We note in passing that this same sequence in half-light radius is present in our C4 cluster sample as in the field. These sequences were interpreted by Ellison et al. (2008b) as a result of differing star formation efficiencies. In Fig. 1 the sample of field galaxies from Ellison et al. (2008b) is used to determine the stellar mass–stellar metallicity relation as a function of \(r\)-band half-light radius. In order to compare the result with that of Ellison et al. (2008b) we have selected those galaxies for which both stellar and nebular abundances can be reliably determined (see the criteria above). We plot the mass–metallicity relation for this sample of 6100 galaxies in Fig. 1, divided into two bins of \(r_h\). Following Ellison et al. (2008b), we calculate the median value of \(r_h\) for each mass bin. Fig. 1 confirms the dependence of the stellar mass–nebular metallicity relation on \(r_h\), but also shows that no such dependence is present in the stellar mass–stellar metallicity relation.

The stellar mass–nebular metallicity relation in close pairs of galaxies has recently been studied by Ellison et al. (2008a) and Michel-Dansac et al. (2008). Both papers find that close pairs of galaxies have a systematically lower metallicity at a given stellar mass than a control sample, by about 0.05 dex (with the exception of the less massive galaxy in disparate mass interactions which may have an enhanced metallicity). Ellison et al. (2008a) also showed that this offset is dependent on half-light radius, with the smallest paired galaxies exhibiting the largest offset to low metallicities. A similar effect is seen in the luminosity–nebular metallicity relation, although with a slightly larger metallicity offset (~0.1 dex; Kewley et al. 2006; Ellison et al. 2008a) indicating that changes in both metallicity and luminosity are at work. In Fig. 2 we investigate whether the offset in the luminosity–metallicity relation of paired galaxies can be recovered from stellar metallicities. The sample of pairs includes galaxies with close companions within a factor of 10 in stellar mass, with velocity separations \(\Delta v < 500\,\text{km}\,\text{s}^{-1}\) and \(r_p < 30\,h_70^{-1}\,\text{kpc}\) open circles) compared with a control sample (solid circles). See Ellison et al. (2008a) for full details of the pairs sample. Unlike the stellar mass–nebular metallicity relation for galaxy pairs (see fig. 15 of Ellison et al. 2008a) there is no clear offset between the pairs and the control.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2}
\caption{The luminosity–stellar metallicity relation for galaxies with close companions \((\Delta v < 500\,\text{km}\,\text{s}^{-1}\) and \(r_p < 30\,h_70^{-1}\,\text{kpc}\), open circles) compared with a control sample (solid circles). See Ellison et al. (2008a) for full details of the pairs sample. Unlike the stellar mass–nebular metallicity relation for galaxy pairs (see fig. 15 of Ellison et al. 2008a) there is no clear offset between the pairs and the control.}
\end{figure}
Figure 3. Properties of galaxies and their host clusters for the refined C4-DR sample (black) and the subset with reliable nebular metallicities (red), where the latter histograms are scaled by a factor of 11 for presentation purposes. The mean values of these histograms are given in Table 1. Although the clusters hosting galaxies with nebular metallicities are indistinguishable from the refined C4-DR4 sample in terms of $\sigma_v$, cluster mass and R200, they contain slightly fewer galaxies on average, have a lower mean stellar mass and tend to be located further from the cluster centre.

Figure 4. Properties of galaxies and their host clusters for the refined C4-DR sample (black) and the subset with reliable stellar metallicities (red), where the latter histograms are scaled by a factor of 4 for presentation purposes. The mean values of these histograms are given in Table 1. Although the clusters hosting galaxies with stellar metallicities are indistinguishable from the refined C4-DR4 sample in terms of $\sigma_v$, cluster mass and R200, they contain slightly more galaxies on average, have a higher mean stellar mass and tend to be located closer to the cluster centre.
Table 1. Properties of the refined C4-DR4 galaxies and the subsets from which reliable nebular and stellar metallicities can be determined.

|                      | All refined C4-DR4 galaxies | C4-DR4 galaxies with nebular metallicities | C4-DR4 galaxies with stellar metallicities |
|----------------------|-----------------------------|-------------------------------------------|------------------------------------------|
| Number of galaxies   | 14,857                      | 1318                                      | 3952                                     |
| Mean redshift        | 0.068                       | 0.070                                     | 0.065                                    |
| Mean # galaxies/cluster | 49.1                        | 45.4                                      | 50.9                                      |
| Mean $\sigma_v$ (km s$^{-1}$) | 543.5                      | 544.2                                     | 546.4                                    |
| Mean R200 (Mpc)     | 1.61                        | 1.61                                      | 1.61                                      |
| Mean RR200 (R200)   | 0.50                        | 0.64                                      | 0.49                                      |
| Mean cluster mass (log $M_{\odot}$) | 14.3                        | 14.3                                      | 14.3                                      |
| Mean galaxy $M_\star$ (log $M_{\odot}$) | 10.4                        | 10.0                                      | 10.6                                      |

Figure 5. The control sample is constructed by iteratively matching the C4-MZ cluster galaxies to SDSS DR4 non-cluster galaxies in redshift, stellar mass, CF and rest-frame $g - r$ colour. There are 21 control galaxies for each of the 1318 C4-MZ cluster galaxies. This figure shows the distribution of the four matched parameters for the C4-MZ cluster galaxies (red) and their control (black), galaxies scaled for presentation purposes.

Table 2. Properties of C4-MZ galaxies and their control galaxies.

|                      | C4-MZ cluster galaxies | Matched control galaxies | KS prob |
|----------------------|------------------------|---------------------------|---------|
| Number of galaxies   | 1318                   | 27,678                    | N/A     |
| Mean redshift        | 0.070                  | 0.070                     | 75 per cent |
| Mean stellar mass ($M_{\odot}$) | 10.0                    | 10.0                      | 52 per cent |
| Mean rest-frame $g - r$ | 0.47                   | 0.47                      | 40 per cent |
| Mean g-band CF       | 30 per cent            | 30 per cent               | 70 per cent |
| Mean g-band $r_h(h_{70}^{-1}$ kpc) | 4.15                   | 4.02                      | 96 per cent |
| Mean log SSFR (yr$^{-1}$) | $-9.70$               | $-9.71$                   | 0.001 per cent |

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| Mean log SSFR (yr$^{-1}$) | $-9.70$               | $-9.71$                   | 0.001 per cent |

Projected separation $r_p < 30 h_{70}^{-1}$ kpc (see Ellison et al. 2008a for further details on the selection of the pairs sample). The luminosity–metallicity relation is shown here since the metallicity offset is larger than for the mass–metallicity relation. However, Fig. 2 shows that there is no offset in the luminosity–stellar metallicity relation for galaxy pairs, relative to a control sample.

3.1 C4 galaxy properties in the mass–metallicity sample

The results of the previous subsection indicate that stellar metallicity is not very sensitive to subtle dependences on galaxy characteristic or environment. The nebular metallicity is therefore adopted for the remainder of this paper. What impact will this have on the number
of galaxies that can be studied, and what biases may be introduced? For example, Cooper et al. (2008) showed that galaxies in the DR4 with nebular abundances are biased towards less rich environments than the full DR4 sample.

In Figs 3 and 4 we show the properties of clusters and their galaxy members for those galaxies in the refined C4-DR4 catalogue which have reliable (in terms of H\textsc{ii} classification, S/N and CF requirements) nebular and stellar metallicities, respectively. There are 1318 galaxies in the refined C4-DR4 with nebular metallicities, compared with 3952 with stellar metallicities. In both figures, the distribution of properties is compared with the \( \sim 15000 \) galaxies in the refined C4-DR4 catalogue. Table 1 lists the mean values for the galaxy and cluster properties of these various samples. Table 1 and Figs 3 and 4 show that galaxies with available nebular or stellar metallicities inhabit different regions in their host cluster and have different stellar mass distributions compared with the full refined C4-DR4 sample. Specifically, galaxies with nebular abundances tend to have lower stellar masses and are rarely located in the centre of the cluster (as measured by R200, the distance from the cluster centre in units of R200). Conversely, galaxies with stellar metallicities have a higher mean stellar mass than all the mean of the full refined C4-DR4 sample and are preferentially located near the cluster centre.

From this exercise we conclude three things.

(i) There is a sufficient number of galaxies with either nebular or stellar metallicities to make a statistical comparison with a control sample.

(ii) Galaxies with either nebular or stellar metallicities can be used to probe clusters with the full range of properties, such as \( \sigma_v \), cluster mass and R200.

(iii) Selecting galaxies with either reliable stellar or reliable nebular metallicities results in a sample that is biased relative to the C4 sample as a whole.

However, since we have also shown that stellar metallicity is relatively insensitive to subtle changes in metallicity, we adopt the gas-phase oxygen abundance as our metric of metallicity. The sample of 1318 galaxies in the refined C4-DR4 sample with reliable nebular abundances is henceforth referred to as the C4 mass–metallicity (C4-MZ) sample, and represents the sample that we will use to investigate the effect of environment on the stellar mass–metallicity

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1 von der Linden et al. (2007) calculate \( \sigma_v \) within R200 using an iterative process that also yields the cluster redshift.
relation. For brevity, the stellar mass–nebular metallicity relation is abbreviated to simply ‘mass–metallicity relation’, or MZR, for the rest of this paper. The results of this subsection indicate that although this sample can probe a representative cross-section of C4 clusters, there is a slight bias towards lower mass clusters (see Table 1) and that this sample underrepresents cluster core environments.

4 THE CONTROL SAMPLE

In order to investigate the MZR of the C4-MZ sample, a control sample must be constructed for comparison. Galaxies in the SDSS DR4 may be considered as control galaxies if they pass the same criteria as the C4-MZ sample (see Sections 2 and 3.1), but are not members of the C4 catalogue.

Galactic stellar mass, luminosity and colour are themselves dependent on environment (e.g. Kauffmann et al. 2004; Baldry et al. 2006; Park et al. 2007). Cooper et al. (2008) also show that metallicity is strongly correlated with colour and luminosity and point out any correlation between local density and metallicity may simply be a manifestation of these interdependences. We therefore construct a control sample that is matched to the cluster sample in galactic properties in order to detect any underlying dependence of metallicity on environment. We construct the control sample in the following way. A ‘pool’ of candidate control galaxies is constructed from the SDSS DR4 which fulfils the same basic requirements enumerated in Section 2, but is not in the cluster sample. For each galaxy in the C4-MZ sample we find the control galaxy that is best matched in stellar mass, redshift, rest-frame $g - r$ colour and CF. Control galaxies can only be selected once; having been identified as a match, they are removed from the potential control ‘pool’. Once a match has been made for every one of the 1318 C4-MZ galaxies, a KS test is performed to confirm that the distribution of each the four matched properties is statistically indistinguishable between the C4-MZ sample and the control sample. If the KS probability is >30 per cent, the matching process is repeated. This process is iterated until the KS probability drops below 30 per cent. In this way, 21 control galaxies are selected for each C4-MZ galaxy (i.e. a total of 27678) before the KS probability becomes unacceptable. Fig. 5 shows the distribution of galaxy properties for the C4-MZ cluster galaxies and the control sample. Table 2 lists the properties of the two samples and the KS probabilities that the two samples are the same. Given the impact discussed above of $r_h$ and SSFR on the mass–metallicity relation, we also compare (although we do not match for) these two properties between the control and C4-MZ samples. The C4-MZ galaxies have a slightly larger mean $r_h$ and SSFR (derived from the aperture-corrected SFRs of Brinchmann et al. 2004). The half-light radii have a high KS probability of being drawn from the same population, even though they were not matched explicitly. On the other hand, the SSFRs of the two samples are statistically inconsistent at a high level. Fig. 5 shows that this statistical inconsistency is due to a tendency for marginally higher SSFRs in our cluster galaxy sample. However, the effect is small, as shown in Table 2 the median SSFR of the C4-MZ sample differs from the control by only 0.01 dex.

Figure 7. The stellar mass–metallicity relation for C4-MZ cluster galaxies (open circles) and their control galaxies (solid circles) for different cuts in half-light radius, binned by mass.
5 The Stellar Mass–Metallicity Relation for C4 Cluster Galaxies

Having selected those C4 cluster galaxies with reliable metallicities (the 1318 C4-MZ galaxies) and compiled a matched sample of 27,678 control galaxies, the MZR in the cluster environment can now be investigated. In Figs 6 and 7 the unbinned and binned MZR for the 1318 C4-MZ galaxies and their control galaxies are shown. The offset between the C4-MZ and control samples is quantified with the parameters $R_{\text{med}}$ and $R_{\text{mean}}$: the median and average difference between cluster and control bins over the mass range $9 < \log M_\star < 11 M_\odot$. Positive values of $R_{\text{med}}$ and $R_{\text{mean}}$ indicate that cluster galaxies are more metal rich than the control. Since half-light radius seems to play an important role in both pairs (Ellison et al. 2008a) and field (Ellison et al. 2008b) galaxies, we also plot the C4 mass–metallicity relation for three cuts in $r_h$. There is a marginal offset towards higher median metallicities by up to 0.04 dex for all $r_h$ cuts, with no strong dependence on half-light radius. This is similar to the small positive offset in metallicity in the highest density environments studied by Mouchine et al. (2007) and Cooper et al. (2008). The small offset towards higher metallicities in the C4-MZ sample relative to the control cannot be explained by the difference in SSFR between the two samples noted in Section 4. As shown in Section 3.1, the SSFRs of C4-MZ galaxies have slightly higher SSFRs than the control sample (see also Fig. 5). However, according to Ellison et al. (2008b), galaxies with higher SSFRs tend to have lower metallicities for a given mass.

Ellison et al. (2008a) showed that the metallicity offset in their pairs study is greater in the luminosity–metallicity plane than in mass–metallicity. This was interpreted as evidence that changes in both luminosity and metallicity are occurring during close galactic passes. We find that the offset in the luminosity–metallicity relation for the C4-MZ galaxies is consistent with that in the MZR, indicating that the star formation event that led to the now metal-enriched ISM is no longer significantly enhancing the magnitude of the galaxy.

Next we investigate whether cluster properties impact the offset of the mass–metallicity relation. The C4-MZ galaxies are divided based on the $\sigma_v$, R200 and mass of its host cluster. In Fig. 8 these MZRs are compared, in each case selecting the control galaxies that were matched to the cluster galaxies in each cut. Fig. 8 shows that the global properties of the cluster do not strongly impact the stellar mass–metallicity relation of the C4-MZ galaxies relative to the control. Visually, there may be a marginally enhanced metallicity offset for clusters with smaller sizes and masses, but this effect is not statistically significant. In Fig. 9 we show the MZR for C4-MZ galaxies at small (RR200 < 0.3 R200) and large (RR200 > 0.8 R200) clustercentric distances. A small excess in metallicity in the C4-MZ clusters is present in both subsets, although it is slightly more pronounced at small values of RR200. There is no correlation between RR200 and either $r_h$ or SSFR that could be causing this difference. We also show in the lowest panel of Fig. 9 the MZR of the C4-MZ clusters split by RR200. There is an offset to higher median nebular metallicities by ~0.03 dex in galaxies within 0.3 R200 relative to galaxies at clustercentric distances above 0.8 R200. However, these two subsamples in RR200 are not necessarily matched in mass, redshift and $g - r$, as is the case for the control sample. None the less, the results of Fig. 9 indicate that the offset in the MZR may

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**Figure 8.** The stellar mass–metallicity relation for C4-MZ cluster galaxies (open circles) and their control galaxies (solid circles). The upper panels show the relationships for galaxies residing in low $\sigma_v$, low R200 and low-mass clusters. The lower panels show the relationships for galaxies residing in high $\sigma_v$, high R200 and high-mass clusters.
be regulated by local factors, such as position within the cluster and not the simple fact of cluster membership; this possibility is investigated further in the next section.

6 LOCAL ENVIRONMENT

6.1 Cluster galaxies with a close companion

As a first test of the relative importance of local environment in the normalization of the MZR, the C4-MZ galaxies are cross-correlated with the sample of close pairs presented in Ellison et al. (2008a). As discussed by Barton et al. (2007), a significant fraction of galaxies with a close companion occur in clusters. In brief, the pairs sample of Ellison et al. contains 2887 galaxies with a companion within a 10:1 stellar mass ratio range, projected separation $r_p < 80 h^{-1}_{70}$ kpc and $\Delta v < 500$ km s$^{-1}$. 95 galaxies (out of 1318) in the C4-MZ sample were matched to the close pairs sample, indicating that these 95 all have a close companion. In Fig. 10 we compare the MZR of these 95 C4-MZ galaxies with a close companion with the 1223 C4-MZ galaxies with no near neighbour and the 27 678 control galaxies. Both the binned and unbinned MZRs are shown, although the close companion sample is only binned at log $M_\star \geq 9.2 M_\odot$ due to small number statistics at lower masses. Fig. 10 shows that those C4-MZ galaxies with close companions have a higher metallicity by $\sim0.05$ dex than C4-MZ galaxies with no neighbour within $r_p = 80 h^{-1}_{70}$ kpc and $\Delta v = 500$ km s$^{-1}$. In fact, the C4-MZ galaxies without companions have metallicities consistent with the control sample. This is consistent with the result of Park et al. (2008) that companions within a few hundred kpc have a more important effect on morphology, star formation and luminosity than the larger scale environment. The lower panel of Fig. 10 shows the distribution of clustercentric radii of the companion/no companion samples. Unsurprisingly, cluster galaxies with a near neighbour reside preferentially at small values of RR200.

In general, the pairs sample is affected by fibre collisions; fig. 1 of Ellison et al. (2008a) shows how these collisions affect completeness as a function of redshift and galaxy separation. Patton & Atfield (2008) find that whilst the overall spectroscopic completeness of the sample is 88 per cent, for separations $<55$ arcsec, this percentage drops to $\sim26$ per cent (on average) at smaller separations. It is therefore likely that there are galaxies with close companions that are currently included among the 1223 non-pair galaxies. Indeed, Barton et al. (2007) used N-body simulations to show that 65 per cent of galaxy pairs are located in haloes with a total of at least four galaxies. They conclude that the majority of pair galaxies are located in the group environment. The offset in the MZR between...
C4-MZ galaxies with and without close companions may therefore be even stronger than shown in Fig. 10.

6.2 Local density estimators

The effect of near neighbours can be further investigated by examining the dependence of the MZR on local galaxy density. Two different density estimates are considered, and for each one the MZR in the most extreme (rich and poor) environments is compared to the matched control galaxies.

6.2.1 The three-dimensional \( n \) density parameter

Cowan & Ivezic (2008) use a three-dimensional density estimator which sums the distances to the 10 nearest galaxies to a given point in space (see Ivezic et al. 2005 for the full details of this formulism):

\[
    n_{10} = \frac{1}{\sum_{i=1}^{10} d_i^3}. \tag{1}
\]

When \( n_{10} \) is calculated at the position of a galaxy, the latter counts as its own closest neighbour, so that \( d_1 = 0 \). Therefore, for our purposes we essentially only consider the nine nearest neighbours:

\[
    n = \frac{1}{\sum_{i=1}^{9} d_i^3}. \tag{2}
\]

This estimator of density is attractive since it uses full three-dimensional information to determine the volume density of galaxies from a certain point. However, it has two main drawbacks. First, there is no correction for fibre collisions, which may lead to an underestimate of the local density in regions rich in projected galaxies. Second, the three-dimensional distances between galaxies do not (cannot) take the peculiar cluster motions into account. The significant velocity dispersions in clusters (see Fig. 3 for the \( \sigma_v \) distribution in our sample) will lead to significant errors in the radial distances between cluster members (a manifestation of the so-called fingers-of-god effect). However, Cowan & Ivezic (2008) show that \( n \) is fairly robust to this effect, being underestimated by up to 10 per cent at the typical redshift of our sample. A third issue which may be of concern is Malmquist bias: for a survey of given apparent magnitude limit, lower redshift galaxies will appear to have more faint neighbours than higher redshift galaxies, due to incompleteness. This can be circumvented by imposing an absolute magnitude cut that yields a volume-limited sample. For example, the density parameter used by Mouhcine et al. (2007) imposes an absolute magnitude cut of \( M_r < -20 \) which yields a volume-limited sample at \( z < 0.085 \) (see also Baldry et al. 2006). Cowan & Ivezic (2008) also apply cuts in luminosity and redshift, but the raw values of \( n \) are not volume limited for our cluster sample. However, as

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\( C \) Cowan & Ivezic (2008) actually use the equation \( n = C [1/(\sum_{i=1}^{10} d_i^3)] \) where the empirically determined value of \( C = 11.48 \) allows the density parameter \( n \) to be translated into a physically meaningful number of galaxies per Mpc\(^3\).
long as the C4-MZ sample galaxies are compared only with their matched control galaxies, Malmquist bias should be unimportant, since the two samples are matched in redshift, colour and stellar mass. That is, the equivalent bias in luminosity and colour selection should apply equally to the 21 control galaxies matched to each C4-MZ galaxy.

### 6.2.2 The two-dimensional Σ density parameter

Mouhcine et al. (2007) use a density estimator based on an average of the projected distances to the fourth and fifth nearest neighbour within 1000 km s\(^{-1}\) (see also Baldry et al. 2006):

\[
\log \Sigma = \frac{1}{2} \log \left( \frac{4}{\pi d^2} \right) + \frac{1}{2} \log \left( \frac{5}{\pi d^2} \right).
\]

For their paper, log \(\Sigma\) was calculated only using neighbour galaxies brighter than \(M_\ast = -20\), in order to obtain a volume-limited sample for \(z < 0.085\). The C4 cluster galaxy sample contains BCGs out to a redshift of \(z = 0.1\) and cluster members out to \(z = 0.11\). The \(\Sigma\) densities are therefore recalculated from equation (3) for \(M_\ast < -20.6\) to yield a volume-limited sample to this higher redshift cut-off. To account for missing spectroscopic redshifts, log \(\Sigma\) is also calculated using photometric redshifts. The final value of log \(\Sigma\) is the average of the spectroscopic redshift value and the value calculated with the inclusion of photometric redshifts (see Baldry et al. 2006 for further discussion). Although not directly affected by the fingers-of-god effect, the calculation of \(\Sigma\) still requires neighbour galaxies to be within 1000 km s\(^{-1}\). The most massive clusters (largest \(\sigma_5\)) in our sample may therefore have their \(\Sigma\) values underestimated. We repeated all of the metallicity analysis presented in the following section for \(\Sigma\) recalculated for galaxies within 2000 km s\(^{-1}\). As expected, the corresponding densities were systematically higher, but they do not affect the conclusions of the MZR analysis. The 1000 km s\(^{-1}\) limit is therefore adopted.

In Fig. 11, the distribution of \(n\) and \(\Sigma\) is shown for both the C4-MZ sample and their matched control galaxies. For reference, we also compare the two density estimators for the cluster and control galaxies. In Fig. 12 the two densities are plotted as a function of clustercentric distance (RR200) for the C4-MZ sample. Although \(\Sigma\) shows a clear dependence on RR200, the relationship between \(n\) and RR200 is very flat. This may be indicative of a combination of the fingers-of-god and fibre incompleteness discussed in the previous section, which lead to an underestimate of \(n\) in the cluster environment.

### 6.3 The impact of local environment on the mass–metallicity relation

In Section 5 we showed that galaxies in the C4-MZ sample have slightly higher metallicities at a given stellar mass compared to the control sample. We also showed that the offset in the MZR does not appear to depend on global cluster properties (RR200, \(\sigma_5\), cluster mass), but that the offset is more pronounced at small clustercentric distances. There is also a strong offset to higher metallicities when a C4-MZ galaxy has a close companion. These results indicate that the offset in the MZR may be driven by local effects within the cluster.

As shown in Fig. 11 cluster galaxies inhabit a wide range of local environment densities, as measured by both \(n\) and \(\Sigma\). We divide the C4-MZ galaxies into those that reside in particularly rich local environments (\(\log n > -1.75\) Mpc\(^{-3}\), \(\log \Sigma > 1.0\) Mpc\(^{-2}\)) and those in relatively poor environments (\(\log n < -3.0\) Mpc\(^{-3}\), \(\log \Sigma < -1.0\) Mpc\(^{-2}\)). In Figs 13 and 14 the MZR of the C4-MZ galaxies in these environmental extremes are compared to their matched controls for the two different density estimators. These figures show that the offset towards high metallicities for a given mass is more pronounced in the high-density environments, as measured by either \(n\) or \(\Sigma\). Indeed, for \(n\) (Fig. 13), the MZR of cluster galaxies in locally poor environments is actually consistent with the control sample. The dependence on environment is emphasized in the lower left-hand panels of Figs 13 and 14 where the metallicities of C4-MZ galaxies in locally rich environments (open points) are systematically higher than cluster galaxies in low-density environments (filled points).

Is the dependence of the MZR on local environment a simple reflection of a dependence on clustercentric distance (e.g. Fig. 9)? For example, in Section 6.1 it was shown that although C4-MZ galaxies with a close companion are more metal rich than both the cluster galaxies with no near neighbour, and the control, they also preferentially reside at lower clustercentric distances. A similar effect is seen in Fig. 14 where the distribution of RR200 is clearly skewed to low values for C4-MZ galaxies in high-density environments. This is not surprising given the anticorrelation between \(\Sigma\) and RR200 previously shown in Fig. 12. Conversely, for \(n\), the distribution of RR200 shown in the lower right-hand panel of Fig. 13 is very similar for the C4-MZ galaxies in both rich and poor environments. As previously discussed, spectroscopic incompleteness due to fibre collisions leads to an underestimate of \(n\) in the densest environments (such as cluster cores), resulting in a flat relationship.
The mass–metallicity relation

Figure 13. The mass–metallicity relation for different cuts in local density, as measured by $n$. In the top panels, solid points are the control galaxies and open points are the C4-MZ galaxies. In the bottom left-hand panel, only C4-MZ galaxies are shown for the same two density cuts (i.e. the open points from the top-right and top-middle panels). The lower right-hand panel shows the clustercentric distances for the C4-MZ galaxies for the two density cuts: log $n < -3$ in black and log $n > -1.75$ in red.

between RR200 and $n$ (see Fig. 12). Therefore, the high and low $n$ samples are probing the same wide range of RR200, so the offset between the two mass–metallicity sequences in Fig. 13 cannot be caused by a dependence on clustercentric distance.

In order to further differentiate between a dependence on RR200 and local density, we calculate the polynomial fit to the MZR of the control galaxies. We derive a good fit with a cubic polynomial of the form

$$\log(O/H) + 12 = 42.243 - 11.6452 \log M_* + 1.30731 (\log M_*)^2 - 0.047577 (\log M_*)^3. \quad (4)$$

The $\Delta \log (O/H)$ of each galaxy in both the cluster and control samples is then calculated as the difference between the measured oxygen abundance and the value inferred from the stellar mass inserted into equation (4). In Fig. 15 we plot the values of $\Delta \log (O/H)$, i.e. the deviation from the best-fitting control MZR, as a function of RR200 (C4-MZ sample only) and $\Sigma$ (C4-MZ and control samples). The top panel of Fig. 15 re-iterates the previous result that the offset of cluster galaxies from the MZR depends on clustercentric distance. This figure shows more clearly that enhanced metallicities are present at RR200 $\lesssim 0.7$ R200. At the smallest clustercentric distances, the median metallicity in the C4-MZ sample is higher than the fit to the control MZR by $\sim 0.035$ dex. In the bottom panel of Fig. 15 we plot the $\Delta \log (O/H)$ for both cluster and control galaxies. As shown in Fig. 11, both the cluster and control galaxies span a similar range in local density (as defined by either $n$ or $\Sigma$). Both the C4-MZ cluster galaxies and the control (non-cluster) sample show enhanced median metallicities by up to 0.04 dex for $\log \Sigma > 0$. This indicates that local density, even outside the cluster environment, can drive the MZR to higher metallicities. Interestingly, the cluster galaxies are consistently (although not significantly) more metal rich at local densities $\log \Sigma > 0$. This may indicate that cluster membership has a minor, secondary effect on a galaxy’s metallicity.

7 SUMMARY AND DISCUSSION

Using a sample of 1318 cluster galaxies with reliable nebular metallicities, we have investigated how the stellar mass–gas phase metallicity relation responds to environmental effects. The main conclusions of this study are as follows.

(i) On average, galaxies in clusters are more metal rich than a control sample matched in mass, $g - r$ colour, redshift and fibre CF by up to 0.04 dex. A similar offset is seen in the luminosity–metallicity relation.

(ii) The offset to higher metallicities for cluster galaxies is independent of the global cluster properties (R200, $\sigma_v$ and cluster mass). However, galaxies at small clustercentric radii (RR200 $< 0.3$ R200) have median metallicities that are higher than galaxies at large clustercentric radii (RR200 $> 0.8$ R200) by 0.03 dex.
Figure 14. The mass–metallicity relation for different cuts in local density, as measured by $\Sigma$. In the top panels, solid points are the control galaxies and open points are the C4-MZ galaxies. In the bottom left-hand panel, only C4-MZ galaxies are shown for the same two density cuts (i.e. the open points from the top-right and top-middle panels). The lower right-hand panel shows the clustercentric distances for the C4-MZ galaxies for the two density cuts: $\log \Sigma < -1.0$ in black and $\log \Sigma > 1.0$ in red.

(iii) Cluster galaxies with a close companion have a higher median metallicity than cluster galaxies without a close companion by $\sim 0.05$ dex.

(iv) Two parametrizations were used to quantify the local density of galaxies in clusters: a three-dimensional estimator, $n$, and a two-dimensional estimator, $\Sigma$. Both density estimators indicate that the metallicity offset between clusters and the matched control sample is larger for richer environments. The difference in median metallicity between cluster galaxies in the richest and poorest environments at a given stellar mass is $0.02$–$0.07$ dex.

(v) Both cluster and control galaxies show a metallicity dependence on local environment.

Taken together, these results indicate that although cluster galaxies have higher average metallicities at a given stellar mass, neither simple cluster membership nor cluster properties seem to drive this effect. Instead, it is apparently local scale processes, such as the presence of a close companion or several near neighbours that leads to an enhanced metallicity. These results are similar in nature to previous findings that galaxy properties are independent of cluster mass, but do depend on clustercentric distance or local overdensity (e.g. Balogh et al. 2004; Martinez, Coenda & Muriel 2008). The median metallicity offset between cluster and control galaxies is only $0.04$ dex, which may explain why previous studies of cluster dwarfs found no clear offset in the MZR with respect to field dwarfs (Vilchez 1995; Lee et al. 2003). The metallicity offset is so subtle that unbinned data (even in a large sample, e.g. Fig. 6) do not clearly demonstrate the metallicity enhancement.

Our conclusions agree with those drawn by Skillman et al. (1996) and Dors & Copetti (2006) who found metal enhancements for some individual galaxies in the Virgo cluster. The statistics of the current study are far superior to that of the Virgo cluster studies which only included nine cluster galaxies. The binned mass–metallicity relations presented here are therefore much less affected by scatter. However, our results are most powerful in probing the average metallicity offset at a given stellar mass, which is distinct from assessing the way a given galaxy responds to its environment. This subtlety is highlighted by the finding of Skillman et al. (1996) and Dors & Copetti (2006) that it is only the gas-deficient Virgo cluster galaxies that show metallicity enhancements. In these cases, the metallicity enhancement is much larger (typically $\sim 0.3$ dex) than our average metallicity offset, even at the highest local overdensities. Zhang et al. (2009) have recently shown that all star-forming galaxies in the SDSS DR4, there is a tendency for gas-deficient galaxies to exhibit higher metallicities at a given stellar mass. Ellison et al. (2008b) also showed that metallicities are high for a given stellar mass for the galaxies with the lowest SSFRs. The low-gas fractions are consistent with the picture that previously efficient star formation has depleted the gas and converted it to stars, leaving a relatively low rate of star formation at the present time.
Gas fractions are not available for the majority of our galaxy sample, although the Arecibo Legacy Fast ALFA (ALFALFA) survey will eventually map approximately 4000 deg$^2$ of the SDSS survey area, covering redshifts out to $z \sim 0.06$. As an alternative measure of gas fraction, we use the calibration of Zhang et al. (2009) which is based on SDSS $g - r$ colour and galaxy surface brightness in the $i$ band. In Fig. 16 the metallicity offset from the control MZR is shown as a function of the ratio of inferred H$_{\text{i}}$-to-stellar mass for both the C4-MZ and control samples. A notable caveat here is that the application of this calibration to cluster galaxies has not yet been tested, so the assumption here is that galaxy colour and surface brightness respond to gas fraction equally in all environments. Enhanced metallicities are seen in both the cluster and control samples when the inferred gas fraction is low, as expected from the results of Zhang et al. (2009). However, the cluster galaxies show an additional systematic metallicity enhancement over the field galaxies. This may be connected with the tentative result of Figure 15 that cluster galaxies are more metal rich than the field at a given overdensity. For example, if the richest environments suffer gas exhaustion through both star formation and stripping (ram pressure/strangulation), e.g. Chung et al. (2007).

The result that galaxies in clusters have a slightly higher metallicity for a given stellar mass than a matched control sample may seem to support the idea of cluster-triggered star formation. However, this is not the only interpretation. If gas is ram pressure stripped from cluster galaxies promptly after entering the cluster, then the deposition of metals into the ISM from the last generation of stars will lead to a relatively high nebular metallicity. The selection of our galaxy sample to have strong emission lines means that they do still contain gas, confirmed by our estimates of gas fraction (see also Tremonti et al. 2004 for alternative derivations of the gas fraction). Simulations indicate that ram pressure stripping can remove up to 80 per cent of a galaxy’s gas within 10$^7$ yr (Abadi, Moore & Bower 1999), although most cluster galaxies undergo more modest gas removal (McCarthy et al. 2008). It is therefore interesting that a similar metallicity enhancement is seen in galaxies in high local densities (as measured by $\Sigma$), but outside of the cluster environment. Ram pressure stripping can remain effective even in groups of galaxies (e.g. Sengupta, Balasubramanayam & Dwarakanath 2007; McCarthy et al. 2008) and tidal forces can disturb or strip gas in more isolated environments. Moreover, as noted in Section 3 in both the field and cluster environments high SSFR does not lead to enhanced metallicities at a given mass. The tendency of our control sample galaxies to have enhanced metallicities, but at a slightly lower level than the cluster galaxies at the same local density and gas fraction, may reflect that both gas depletion through star formation and some stripping process contribute to gas exhaustion in clusters.

Peeples et al. (2008) studied a sample of low-mass, high-metallicity outliers in the MZR which reside in a similar parameter space to some of the C4-MZ galaxies with close companions. However, the metal-rich dwarfs in the Peeples et al. sample are relatively isolated, with no close companions and are not in clusters. Peeples et al. (2008) conclude that these objects are likely to be transitional dwarfs with low gas fractions that are nearing the end of their star-forming lifetimes. Based on the finding that gas-rich and gas-poor dwarfs follow the same MZR, Lee et al. (2008) have argued that most dwarf spheroidals are formed by the removal of gas, a process linked to local environment. However, since the metal-rich outliers of Peeples et al. (2008) are morphologically consistent with dwarf spheroidals, yet have no near neighbours and are not located in clusters, these galaxies may have avoided gas stripping and hence been

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**Figure 15.** $\Delta \log (O/H)$ is the difference between the measured galaxy metallicity and the polynomial fit to the control MZR given in equation (4). The metallicity offset is plotted as a function of local environment density. Open symbols represent C4-MZ cluster galaxies, and solid symbols are the control sample. The positive difference for control galaxies at high local densities indicates that cluster membership is not the dominant factor in driving the cluster galaxies to enhanced metallicities.

**Figure 16.** $\Delta \log (O/H)$ is the difference between the measured galaxy metallicity and the polynomial fit to the control MZR given in equation (4). The metallicity offset is plotted as a function of inferred H$_{\text{i}}$-to-stellar mass ratio. Open symbols represent C4-MZ cluster galaxies, and solid symbols are the control sample. Gas-poor galaxies in both the cluster and control samples show positive metallicity offsets towards lower gas fractions.
able to evolve peacefully and achieve their relatively high metallicities. It therefore appears that there may be more than one route to getting (metal) rich.

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