The role of environment in the mass–metallicity relation

Michael C. Cooper,† Christy A. Tremonti,† Jeffrey A. Newman‡ and Ann I. Zabludoff

1Steward Observatory, University of Arizona, 933 N. Cherry Avenue, Tucson AZ 85721, USA
2Department of Physics and Astronomy, University of Pittsburgh, 401-C Allen Hall, 3941 O’Hara Street, Pittsburgh PA 15260, USA

ABSTRACT

Using a sample of 57,377 star-forming galaxies drawn from the Sloan Digital Sky Survey, we study the relationship between gas-phase oxygen abundance and environment in the local Universe. We find that there is a strong relationship between metallicity and environment such that more metal-rich galaxies favour regions of higher overdensity. Furthermore, this metallicity–density relation is comparable in strength to the colour–density relation along the blue cloud. After removing the mean dependence of environment on colour and luminosity, we find a weak, though significant, residual trend between metallicity and environment which is largely driven by galaxies in high-density regions, such as groups and clusters. We discuss the potential source of this relationship between metallicity and local galaxy density in the context of feedback models, with special attention paid to quantifying the impact of environment on the scatter in the mass–metallicity relation. We find that environment is a non-negligible source of scatter in this fundamental relation, with \( \lesssim 15\) per cent of the measured scatter correlated with environment.

Key words: galaxies: abundances – galaxies: evolution – galaxies: fundamental parameters – galaxies: statistics – large-scale structure of Universe.

1 INTRODUCTION

Gas-phase metallicity is one of the most fundamental characteristics of a galaxy, affecting the evolution of its stellar population and the composition of its interstellar medium (ISM). Moreover, metallicity indirectly traces a galaxy’s star formation history and reflects the balance of several important physical processes: the release of metals into the ISM via supernovae and stellar winds, the ejection of gas via galactic outflows and the accretion of gas on to the galaxy from the surrounding environs. Understanding how metallicity evolves, especially in relation to other fundamental galaxy properties, is essential in isolating the physical mechanisms that drive star formation and, more generally, galaxy evolution.

As first observed by Lequeux et al. (1979), metallicity is strongly correlated with galaxy stellar mass, such that more massive galaxies are more metal rich in composition. Due to the relative ease of measuring luminosities versus stellar masses, many subsequent studies extended this early work to larger samples of galaxies by studying the correlation between luminosity and metallicity (e.g. Skillman, Kennicutt & Hodge 1989; Brodie & Huchra 1991; Zaritsky, Kennicutt & Huchra 1994; Garnett 2002; Kobulnicky et al. 2003; Lamareille et al. 2004). Using large data sets from surveys such as the Sloan Digital Sky Survey (SDSS, York et al. 2000), more recent analyses have brought measurements of the luminosity–metallicity and mass–metallicity relations on par with each other, measuring relations that span more than 10 mag in optical luminosity and six orders of magnitude in stellar mass, ranging from dwarf galaxies up to the most massive star-forming systems (e.g. Pilyugin & Ferrini 2000; Lee, McCall & Richer 2003; Tremonti et al. 2004; Shapley et al. 2005; Erb et al. 2006; Lee et al. 2006).

Both the luminosity–metallicity and mass–metallicity relations show significant scatter, with only half the observed spread in the metallicity distribution at fixed stellar mass being due to observational error and an even greater (\( \sim 50\) per cent greater) scatter measured for the luminosity–metallicity relation (Tremonti et al. 2004). Various studies have pointed to physical sources of the scatter in these fundamental relations. For example, studying a sample of ultraviolet-selected (UV-selected) galaxies at \( z < 0.4\), Contini et al. (2002) find that these systems are offset from the luminosity–metallicity relation due to a recent starburst that has enriched their ISM and decreased their mass-to-light ratios, moving them off of the median trend. As illustrated by Tremonti et al. (2004),
however, these results suggest that the relationship between metallicity and stellar mass (and not luminosity) is more fundamental; even when accounting for variations in mass-to-light ratio due to dust attenuation and observing at redder wavelengths so as to minimize the impact of newly formed stars on the measured luminosity, the scatter in the luminosity–metallicity relation is still greater than that observed between stellar mass and metallicity.

By analysing the correlations between the scatter in the mass–metallicity relation and other galaxy properties (e.g. rest-frame colour, inclination, photometric concentration, etc.), Tremonti et al. (2004) point to a potential connection with stellar surface mass density, $\mu_*$, such that galaxies with higher surface densities are more metal-rich relative to galaxies of similar stellar mass (see also Ellison et al. 2008a). This trend is potentially explained by a scenario where galaxies with higher surface densities have converted more of their gas reservoirs into stars and thereby elevated their metallicity. In conflict with this picture, however, Tremonti et al. (2004) find no significant correlation between scatter in the mass–metallicity relation and morphology (as traced by the concentration).

Local galaxy density (i.e. the local ‘environment’) could act as an alternate source of the scatter in the mass–metallicity relation. Supernovae are predicted to enrich the intergalactic medium (IGM) over roughly Mpc scales (e.g. Adelberger et al. 2005), which would impact the metallicity of nearby galaxies in high-density environments. Similarly, in clusters of galaxies, intracluster supernovae may inject a significant quantity of metals into the intracluster gas (Dainoinko et al. 2004), which is subsequently accreted on to cluster members, thereby raising their metallicity.

Galaxies in high-density regions should collapse and form stars earlier than their counterparts in low-density environments; studies of the colour–density relation show that galaxies with older stellar populations favour higher density environments at $z \sim 0$ (e.g. Balogh et al. 2004a,b; Blanton et al. 2005a) and $z \sim 1$ (e.g. Smith et al. 2005; Cooper et al. 2006). Thus, galaxies might be expected to become more metal rich sooner in high-density regions.

Direct evidence for the potential role of environment in shaping the metallicity of a galaxy is found in observational work by Kewley, Geller & Barton (2006), which shows that galaxy interactions, common in galaxy pairs and groups (Cavaliere, Colafrancesco & Menci 1992), may lead to inflows that drag metal-poor gas to the galaxy centre, decreasing the gas-phase metallicity in such systems (see also Ellison et al. 2008b). The analysis of Kewley et al. (2006), however, probes a limited range of extreme environments (focusing on pairs at close separations), which provides a vastly incomplete view of the role of environment. Similarly, analysis of 41 metal-rich, low-mass galaxies by Peeples, Pappe & Stanek (2008), finds that such outliers on the mass–metallicity relation tend to be isolated and undisturbed systems (i.e. reside in low-density environments). Though, this work is clearly limited by its small sample size and the restricted mass range probed.

In this paper, we utilize data from the SDSS to study the relationship between metallicity and environment among the nearby, star-forming galaxy population. Specifically, we inspect the correlation between metallicity and environment in comparison to well-established correlations between environment and properties such as rest-frame colour. In addition, we examine the potential impact of environment on the scatter in the mass–metallicity relation. In Section 2, we outline the data set used in this analysis. In Sections 3, 4 and 5, we present our results on the relationship between metallicity and environment at $z \sim 0.1$. We then endeavour to quantify the role of environment in driving the scatter in the mass–metallicity relation in Section 6. In Sections 7 and 8, the results of this analysis are then discussed and summarized. Unless otherwise noted, all work in this paper employs a flat, $\Omega_m = 0.7, \Omega_m = 0.3, h = 1$ cosmology.

## 2 Data Sample

To study the relationship between local galaxy environment and various galaxy properties, including metallicity, we utilize data drawn from the SDSS public Data Release 4 (DR4, Adelman-McCarthy et al. 2006), as contained in the NYU–Value-Added Galaxy Catalog (NYU–VAGC, Blanton et al. 2005b). We restrict our analysis to the redshift regime $0.05 < z < 0.15$ in an effort to probe a broad range in galaxy luminosity, with large sample size, while minimizing aperture effects related to the finite size (3 arcsec) of the SDSS fibers. In addition, we limit our sample to SDSS fiber plates for which the redshift success rate for targets in the main spectroscopic survey is 80 per cent or greater.\footnote{Selecting SDSS fiber plates with a redshift success rate of $\geq 80$ per cent excludes only $\sim 5$ per cent of the plates included in the SDSS DR4.}

### 2.1 Measurements of local galaxy environments

We estimate the local galaxy overdensity, or ‘environment’, in the SDSS using measurements of the projected third-nearest neighbour surface density ($\Sigma_3$) about each galaxy, where the surface density depends on the projected distance to the third-nearest neighbour, $D_{p,3}$, as $\Sigma_3 = 3/(\pi D_{p,3}^2)$. In computing $\Sigma_3$, a velocity window of $\pm 1000 \, \text{km s}^{-1}$ is employed to exclude foreground and background galaxies along the line of sight. Tests by Cooper et al. (2005) found this environment estimator to be a robust indicator of local galaxy density within deep surveys.

To correct for the redshift dependence of the SDSS sampling rate, each surface density value is divided by the median $\Sigma_3$ of galaxies at that redshift within a window of $\Delta z = 0.02$; this converts the $\Sigma_3$ values into measures of overdensity relative to the median density (given by the notation $1 + \delta_3$ here) and effectively accounts for redshift variations in the selection rate (Cooper et al. 2005). Finally, to minimize the effects of edges and holes in the SDSS survey geometry, we exclude all galaxies within $1 \, h^{-1} \, \text{Mpc}$ (comoving) of a survey boundary. For further details regarding the computation of galaxy environments in the SDSS, we direct the reader to Cooper et al. (2006) and Cooper et al. (2008).

### 2.2 Measurements of rest-frame colour, absolute magnitude and stellar mass

We compute rest-frame $g - r$ colours, absolute $r$-band magnitudes ($M_r$) and stellar masses from the apparent, petrosian $ugriz$ magnitudes in the SDSS DR4, using the kcorrect $K$-correction code (version v4.1.2) of Blanton & Roweis (2007, see also Blanton et al. 2003a). The template spectral energy distributions (SEDs) employed by kcorrect are based on those of Bruzual & Charlot (2003). To estimate stellar masses, the best-fitting SED given the observed $ugriz$ photometry and spectroscopic redshift is used to directly compute the stellar mass-to-light ratio ($M_*/L$), assuming a Chabrier (2003) initial mass function. We have also employed the stellar mass estimates of Kauffmann et al. (2003a), which do not rely on fitting SEDs to the SDSS photometry; instead they have been derived by fitting to stellar absorption-line indices, measured from the observed SDSS spectra, while also attempting to correct...
for attenuation due to dust. Using these alternate stellar mass, values produce no significant changes in the results of our analyses. Finally, all magnitudes within this paper are given in the AB system (Oke & Gunn 1983).

2.3 Measurements of spectral properties: metallicity and star formation rate

To study the metallicities of the SDSS galaxies, we utilize oxygen abundances, $12 + \log_{10}(O/H)$, from Tremonti et al. (2004), which have been derived by statistically comparing the fits of nebular emission lines in the SDSS spectra to the models of Charlot & Longhetti (2001). The sample is limited to only those sources with H$\beta$, H$\alpha$ and [N ii] $\lambda$6584, all detected at a 5$\sigma$ level. Furthermore, we constrain our analysis to the star-forming galaxy sample, excluding those objects hosting an active galactic nucleus (AGN) according to the conservative line-diagnostic criteria of Kauffmann et al. (2003b). By also requiring accurate environment measures, as described above, we arrive at a final star-forming galaxy sample including 57 377 sources at $0.05 < z < 0.15$. A distribution of the sample in colour–magnitude space is shown in Fig. 1. By excluding quiescent galaxies and AGN, the star-forming sample is biased against galaxies residing on the red end of the blue cloud or the red sequence. In Fig. 2, we also show the distribution of environment measures for the star-forming sample relative to that for the full SDSS sample. While the star-forming galaxies are biased towards lower overdensities (consistent with a sample dominated by blue galaxies), the sample still spans a full range of environments, from voids to clusters.

To probe the ongoing star formation activity in this sample, we employ the aperture-corrected star formation rates (SFR) of Brinchmann et al. (2004), which are estimated by fitting models to the nebular emission features in the SDSS spectra. For the star-forming galaxy population, these SFRs show excellent agreement with UV-based SFR estimates (Salim et al. 2007). Note that the SFR values of Brinchmann et al. (2004) are estimated using $h = 0.7$ rather than $h = 1$.

3 THE DEPENDENCE OF MEAN ENVIRONMENT ON METALLICITY

A wide variety of galaxy properties at low and intermediate redshift have been shown to correlate with environment. For instance, at $z < 1$, blue, star-forming galaxies are found to reside in regions of lower galaxy density in comparison to red and dead systems (e.g. Balogh et al. 1998; Kauffmann et al. 2004; Cooper et al. 2006; Cucciati et al. 2006; Capak et al. 2007). Moving beyond direct studies of the colour–density or morphology–density relations, Blanton et al. (2005a) analysed the relationship between environment and the luminosities, surface brightnesses, rest-frame colours and structural characteristics (Sérsic indices) of nearby galaxies in the SDSS sample. Among this set of galaxy properties, they found that colour and luminosity are the pair that prove to be most predictive of the local environment. That is, rest-frame colour and luminosity are the two characteristics most closely related to the galaxy density, as measured on small ($\sim 1 h^{-1}$ Mpc) scales. Furthermore, at fixed colour and luminosity, they found no significant trend between local galaxy density and surface brightness or Sérsic index among the star-forming population – although, for the full SDSS sample, there is some residual correlation observed at high luminosities, likely driven by rare, very luminous, red systems in dense environments such as brightest cluster galaxies (Blanton et al. 2005a).

Like surface brightness and Sérsic index, metallicity is strongly correlated with colour and luminosity, such that brighter and redder sources on the blue cloud tend to have higher metal abundances. This trend is clearly evident in the top panel of Fig. 3, where we show the mean gas-phase oxygen abundance, $12 + \log_{10}(O/H)$, as a function of rest-frame colour and absolute magnitude for the SDSS star-forming sample. Not surprisingly, when we examine the relationship between metallicity and environment, we find a strong trend that includes contributions from the correlations between (i) metallicity, colour and luminosity and (ii) colour, luminosity, and environment. As shown in the bottom portion of Fig. 3, the typical environment
increases in overdensity for galaxies with higher metallicities.\textsuperscript{2} This metallicity–environment relation agrees with the well-established colour–density relation along the blue cloud (Hogg et al. 2003; Blanton et al. 2005a), where the mean galaxy density increases with colour.

\textsuperscript{2}The local environment is thought to influence galaxy properties, such that galaxy properties are typically studied as a function of environment. In Fig. 3(b), however, we plot the dependence of mean environment on metallicity and not vice versa for one significant reason: measurements of environment are significantly more uncertain than measures of metallicity. Thus, binning galaxies according to local overdensity would yield significant correlation between neighbouring environment bins, which would consequently smear out the underlying correlation between metallicity and local galaxy overdensity.

While the trend evident in Fig. 3(b) may not be surprising, the strength of this environment–metallicity relation is very striking when compared to that seen between environment and colour, luminosity, stellar mass or SFR. As shown in Figs 3(b) and 4, the metallicity–density relation is roughly comparable in strength to the colour–density relation amongst the star-forming population. In addition, the dependence of mean overdensity on luminosity, stellar mass and SFR is all weaker than that observed with metallicity. Along the blue cloud, there is clearly a strong relationship between gas-phase oxygen abundance and the local galaxy environment.

### 4 REMOVING THE MEAN COLOUR–LUMINOSITY–ENVIRONMENT RELATION

Given the relationships between metallicity, colour and luminosity, it would be reasonable to expect that the strong relationship between local galaxy density and metallicity is entirely contained in the colour–luminosity–environment relation (within the precision of our measurements), such that there is no residual trend between metallicity and environment at fixed colour and luminosity – similar to the findings of Blanton et al. (2005a) for surface brightness and Sérsic index. To probe the dependence of environment on metallicity at fixed colour and luminosity, we fit and remove (subtract) the dependence of mean environment on rest-frame colour and absolute magnitude. Fig. 5(a) shows the mean overdensity as a function of rest-frame \( g - r \) colour and \( r \)-band absolute magnitude, or \( <\log_{10}(1 + \delta_{3})|g - r, M_{r}> \), for the SDSS star-forming sample. There is a clear colour–density trend, where the mean overdensity increases with colour along the blue cloud. To remove this relationship of environment to colour and luminosity, we subtract the mean overdensity at the colour and luminosity of each galaxy from the measured overdensity:

\[
\Delta_{3} = \log_{10}(1 + \delta_{3}) - <\log_{10}(1 + \delta_{3})|g - r, M_{r}> ,
\]

where the distribution of mean environment with colour and absolute magnitude, \( <\log_{10}(1 + \delta_{3})|g - r, M_{r}> \) (see Fig. 5(a)), is median smoothed on \( \Delta(g - r) = 0.15 \) and \( \Delta M_{r} = 0.6 \) scales prior to subtraction.

An alternate method of effectively removing the colour–luminosity–environment relation from our analysis would be to study the metallicity–environment relation in bins of rest-frame colour and absolute magnitude (or in bins of stellar mass). This approach, however, can be far less sensitive, since dividing the sample into such restricted subsets reduces the signal-to-noise ratio of any trend that occurs across the entire colour–magnitude distribution (i.e. spans the blue cloud). In Section 7.3, we return to this point in comparison to other recent, related analyses.

The ‘residual’ environment, \( \Delta_{3} \), quantifies the overdensity about a galaxy relative to galaxies of similar colour and luminosity, where values of \( \Delta_{3} \) greater than zero correspond to galaxies in environments more overdense than the typical galaxy with like star formation history (i.e. like \( g - r \) and \( M_{r} \)). Fig. 5(b) shows the dependence of mean \( \Delta_{3} \) on colour and luminosity; no significant colour or luminosity dependence is evident. Furthermore, Fig. 5(c) displays the distribution of \( \langle \Delta_{3} \rangle \) values from Fig. 5(b), illustrating that deviations from \( \langle \Delta_{3} \rangle = 0 \) are small.

While the \( \Delta_{3} \) statistic effectively removes the mean colour–density and luminosity–density relations from the data set, this measure of the residual environment is only a small perturbation to the ‘absolute’ overdensity, \( \log_{10}(1 + \delta_{3}) \). As shown in Fig. 6, the \( \Delta_{3} \) value for each galaxy in our sample is still strongly...
correlated with the corresponding \(\log_{10}(1 + \delta_3)\) measurement. This close correlation is, at least in part, due to the large uncertainty in individual overdensity, \(\log_{10}(1 + \delta_3)\) measures. The bias towards \(\Delta_3 > \log_{10}(1 + \delta_3)\) is a product of the colour–density relation and the inclusion of red-sequence galaxies in the measurement of galaxy overdensities (see Section 2.1).

5 THE RESIDUAL DEPENDENCE OF ENVIRONMENT ON METALLICITY

By studying the dependence of residual environment, \(\Delta_3\), on various galaxy properties, we can determine whether there is any excess trend with environment beyond that contained in the colour–luminosity–environment relation. As a sanity check, in Fig. 7(a), we examine the dependence of mean \(\Delta_3\) on colour or absolute magnitude, and confirm that there is no trend with these properties, as expected. We likewise test for any dependence of residual environment on stellar mass or SFR (see Fig. 7b).

We find no significant trend of \(\Delta_3\) with colour, luminosity, stellar mass or SFR. This result is clearly to be expected for colour and luminosity, by construction. Even the relatively tight relationship between the combination of \(g - r\) and \(M_r\) with \(M_\ast\) (e.g. Kauffmann et al. 2003a; Cooper et al. 2007), it is also not surprising to find no residual trend with stellar mass, as an additional test.

When using the stellar mass values of Kauffmann et al. (2003a), which were derived from fits to stellar absorption features in the SDSS spectra rather than computed directly from the SDSS photometry (see Section 2.2), we find a similar lack of any trend. For SFR, which exhibits a weaker correlation with absolute environment, \(\log_{10}(1 + \delta_3)\), we find no evidence for a relationship with residual environment, \(\Delta_3\), much like the lack of secondary environment dependencies on surface brightness or Sérsic index found by Blanton et al. (2005a).

Turning our attention towards metallicity, we examine the dependence of mean residual environment, \(\Delta_3\), on gas-phase oxygen abundance; as shown in Fig. 8, there is a striking trend such that more metal-rich galaxies typically reside in more overdense environments relative to galaxies of like colour and luminosity (i.e. of like stellar mass). While the residual environment statistic, \(\Delta_3\), has no relationship with colour, luminosity, stellar mass or SFR, it is strongly related to metallicity. In particular, this trend seems to be most significant among the most metal-rich galaxies [12 + \(\log_{10}(O/H) > 9.15\)].

Given that the residual environment closely traces the absolute overdensity measurement (see Fig. 6), it is interesting to examine this residual metallicity–environment relation from the
For the 57,377 galaxies in the star-forming population, we plot the relationship between the ‘residual’ environment, $\Delta_3$, and the ‘absolute’ environment, $\log_{10}(1 + \delta_3)$. For a definition of the $\Delta_3$ statistic, refer to equation (1). The residual environment roughly traces the absolute overdensity, with the scatter showing no significant dependence on environment.

opposite perspective. Fig. 9 shows the dependence of mean gas-phase oxygen abundance on the residual environment within the SDSS star-forming sample. While studying mean relations from this perspective is physically intuitive, binning galaxies according to environment (residual or absolute) introduces significant correlation between neighbouring environment bins, due to the significant uncertainties in measuring local galaxy densities [$\sigma_{\log(1 + \delta_3)} \sim 0.5$ versus $\sigma_{12 + \log_{10}(O/H)} \sim 0.1$], which can therefore weaken or erase any underlying trends. Despite this smearing effect, we still find a strong trend, where the mean metallicity increases dramatically in higher density regions ($\Delta_3 \gtrsim 1$); this suggests that the residual metallicity–environment relation is dominated by phenomena occurring in overdense regions (such as groups and clusters), rather than underdense environments.

6 SCATTER IN THE MASS–METALLICITY RELATION

The excess correlation between metallicity and environment, beyond that contained in the colour–luminosity–environment relation (or stellar mass–environment relation), strongly suggests that the shape or normalization of the mass–metallicity relation must depend on local galaxy environment. This suggestion is confirmed in Fig. 10, where we show fits to the mass–metallicity relation, computed using galaxies in the extreme quintiles of the environment distribution. Over the entire range of stellar masses probed by the SDSS sample, the mass–metallicity relation is biased towards higher metallicities in higher density regions.

While Fig. 10 clearly illustrates the environment dependence of the mass–metallicity relation, showing an offset towards higher metallicity in higher density regions, it does not quantify the level to which environment contributes to the scatter in this fundamental relationship. To this end, we examine the correlation between environment and the residual metallicity, $\Delta_{O/H} = 12 + \log_{10}(O/H) - f(M_*)$, measured relative to the median mass–metallicity relation, $f(M_*)$, as determined by the full star-forming sample.

As shown in Fig. 11, the average residual metallicity exhibits a clear dependence on environment, such that galaxies in overdense regions are biased towards higher metallicities than galaxies of like stellar mass. This result is effectively a rephrasing of the trend shown in Figs 9 and 10, except that in this form we are able to subtract the average offset in the mass–metallicity relation due to environment, yielding a quantity

$$\epsilon = 12 + \log_{10}(O/H) - \langle \Delta_{O/H} | \Delta_3 \rangle,$$

which gives the metallicity corrected for the observed environment dependence.

Figure 6. For the 57,377 galaxies in the star-forming population, we plot the relationship between the ‘residual’ environment, $\Delta_3$, and the ‘absolute’ environment, $\log_{10}(1 + \delta_3)$. For a definition of the $\Delta_3$ statistic, refer to equation (1). The residual environment roughly traces the absolute overdensity, with the scatter showing no significant dependence on environment.

Figure 7. Left-hand panel: the dependence of mean residual environment, $\Delta_3$, on rest-frame colour and absolute magnitude, as given by the black circles plus solid line and red diamonds plus dashed line, respectively. Right-hand panel: similar to the plot on the left-hand side, but for stellar mass, $M_*$ (black circles and solid line) and SFR (red diamonds and dashed line). After removing the mean dependence of environment on colour and luminosity, we find no significant residual trend with colour, luminosity, stellar mass or SFR.
The dependence of mean residual environment, $\Delta_3$, on metallicity. We find a strong trend with metal-rich galaxies being found, on average, in regions of higher overdensity relative to galaxies of like colour and luminosity.

Subtracting (in quadrature) the measured scatter in the mass–$\epsilon$ relation from the scatter in the mass–metallicity relation, we find that environment is correlated with $\geq 15$ per cent of the observed scatter in the mass–metallicity relation. This environment dependence is evident, with comparable strength, at all stellar masses. As discussed in Sections 4 and 5, the relatively large uncertainties in the environment measurements can smear out the underlying correlation between metallicity and environment, thereby weakening the measured contribution of environment to the scatter in the mass–metallicity relation. Thus, local environment is correlated with at least 15 per cent of the observed scatter, which represents a non-negligible contribution to the total intrinsic scatter.

While we find a significant offset in the normalization of the mass–metallicity relation in different environments, we do not detect any environment-dependent variation in the intrinsic scatter. As shown in Fig. 12, the measured root-mean-square (rms) scatter in the mass–metallicity relation is independent of environment, at a constant level of roughly $\sigma_{\text{rms}} \sim 0.1$. This suggests that whatever is dominating the intrinsic scatter in the mass–metallicity relation is independent of local galaxy overdensity.

7 DISCUSSION

7.1 Potential selection effects

While we utilize the relatively conservative line-diagnostic criteria of Kauffmann et al. (2003b) for excluding AGN from our sample, any significant amount of contamination from AGN emission in the integrated galaxy spectra could potentially impact the oxygen abundance measurements, biasing them towards high (or low) metallicity. If AGN are strongly correlated with a given environment (e.g. if they are preferentially found in high-density regions), then the metallicity–density relation could be (at some level) a product of this underlying AGN–environment correlation. Of particular interest is the relationship between Low Ionization Nuclear Emission-line Regions (LINERs, Heckman 1980) and environment as low-level AGN such as LINERs are more likely to contaminate the star-forming sample than their more powerful Seyfert counterparts.

Using the SDSS data set, several studies of the relationship between AGN activity and environment have uncovered no significant correlation between low-level AGN activity and local galaxy density. For example, Miller et al. (2003) found that the fraction of AGN shows no variation with environment within the SDSS early data release (Stoughton et al. 2002), a result supported by later work using the larger DR4 data set (Sorrentino, Radovich & Riffatto 2006). While analysis by Montero-Dorta et al. (2008) shows that the fraction of LINERs and Seyferts on the red sequence is potentially lower in high-density environments locally, this result may not be representative of the environments of LINERs in the blue cloud (i.e. among the star-forming population). In partial agreement with the results of Montero-Dorta et al. (2008), Kauffmann et al. (2004) conclude that the fraction of galaxies hosting a powerful
dominated systems are typically more metal rich (e.g. Vila-Costas & Edmunds 1992; Zaritsky 1993; Zaritsky et al. 1994). An analogous trend is found when studying stellar metallicities among a more diverse galaxy population (Gallazzi et al. 2008). Any relationship between metallicity and environment separate from that observed with stellar mass could therefore be a derivative of the well-known morphology–density relation (e.g. Davis & Geller 1976; Dressler 1980).

Given the strong correlations between luminosity, colour and morphology on the blue cloud, the existence of a significant correlation between residual environment, \( \Delta_3 \) and morphology is unlikely when none is found with luminosity or rest-frame colour. However, we investigate this possibility using the Sérsic indices of Blanton et al. (2003b, 2005a). While the Sérsic index is a measure of morphology derived from the fit of only a single component to the galaxy’s radial profile (versus bulge-disc decomposition, for example), we find no dependence of mean residual environment on Sérsic among our sample. Furthermore, recent analysis of star-forming galaxies in the SDSS found that the mass–metallicity relation shows no dependence on bulge fraction (Ellison et al. 2008a). Plus, as stated in Section 1, Tremonti et al. (2004) found no correlation between the scatter in the mass–metallicity relation and galaxy concentration. Thus, we conclude that the portion of the scatter in the mass–metallicity relation correlated with environment is not attributable to variations in galaxy morphology.

Finally, by restricting our galaxy sample to SDSS galaxies for which we are able to accurately measure the gas-phase metallicity, we have effectively applied a signal-to-noise ratio selection cut. Thus, our sample of star-forming galaxies is not strictly limited according to SFR or even by location in the colour–magnitude diagram. To test the impact of employing such restrictions, we further restrict to two subsamples: (i) galaxies with SFR \( > 3 M_\odot/\text{yr} \) and (ii) a volume-limited sample of galaxies located on the blue cloud according to the simple colour–magnitude limits \( M_r < -20.6 \) and \( g - r < 0.65 \). While both of these samples are limited in size, for each we still find a significant dependence of metallicity on environment, in agreement with the results presented in Sections 5 and 6.

7.2 Theoretical interpretation

As discussed in Section 1, gas-phase metallicity and its relationship with stellar mass within the star-forming population is directly connected to feedback associated with star formation, as metals are added to the ISM via supernovae and as gas is ejected via outflows and accreted from the surrounding IGM. The presence of outflows in star-forming galaxies has been supported by a variety of observations (e.g. Lehner & Heckman 1996; Frye, Broadhurst & Benítez 2002; Weiner et al. 2008), but the physics of this feedback mechanism remains poorly understood.

In an attempt to explain the mass–metallicity relation, early feedback models (e.g. Dekel & Silk 1986; Cole 1991; Dekel & Woo 2003) employed energy-driven winds, powered by supernovae explosions (Larson 1974), to expel metals from low-mass galaxies. Such models, however, fail to include the role of winds in more massive systems (\( M_\star \geq 10^{10} M_\odot \)), while observational work has shown outflows to be common at galaxy stellar masses of \( \geq 10^{11} M_\odot \) (e.g. Shapley et al. 2003; Rupke, Veilleux & Sanders 2005; Weiner et al. in preparation).

In contrast, the models of Springel & Hernquist (2003a) incorporate winds at all mass scales, but their simple prescription relies on winds of a constant velocity (484 km s\(^{-1}\)).
2003b), independent of galaxy mass. In disagreement with this approach, recent observations by Martin (2005) show outflow velocities to scale approximately linearly with circular velocity (i.e. increase in \( M_\star \)). Furthermore, simple wind approximations such as that of Springel & Hernquist (2003b) fail to reproduce some properties of the IGM at higher redshift (e.g. underpredicting metal enrichment, Aguirre et al. 2005) and the mass–metallicity relation at \( z \sim 2 \) (Finlator & Davé 2008).

Recent work by Finlator & Davé (2008) has ventured to take a more detailed approach to modelling the feedback in star-forming galaxies (see also Oppenheimer & Davé 2006). In their model, outflows are pushed by momentum-driven winds (Murray, Quataert & Thompson 2005), where momentum is deposited into the ISM by coupling with the radiation from star formation through dust absorption and where the wind speed scales with the galaxy’s circular velocity. Rather than assuming a wind that is driven in all directions (such as that of Springel & Hernquist 2003a), Finlator & Davé (2008) model polar outflows with constrained opening angles (\( \sim 45^\circ \)) such that the resulting outflows much more closely imitate those observed locally (e.g. Veilleux, Cecil & Bland-Hawthorn 2005).

In addition to assuming a wind speed that scales linearly with rotational speed, the Finlator & Davé (2008) model assumes that the mass-loading factor – the rate of mass ejection divided by the SFR – is inversely related to the circular velocity. These scaling relations evolve naturally for momentum-driven winds (Murray et al. 2005) and are in rough agreement with results from other detailed feedback models (e.g. Brooks et al. 2007; Kobayashi, Springel & White 2007). Within this theoretical framework, the gas-phase metallicity at any epoch depends on (i) the mean metallicity of accreted gas and (ii) the mass-loading factor (see equation 20 of Finlator & Davé 2008).

In this model, the observed trends between metallicity and environment would require either higher enrichment of the gas flowing into galaxies in overdense regions and/or lower mass-loading factors in high-density environments. There are many environment-dependent physical mechanisms that could yield the former; for instance, galaxy mergers, harassment, and ram-pressure stripping in groups and clusters can strip enriched gas from member and infalling galaxies, thereby inflating the metal content of the local gas reservoir relative to the gas supply of roughly primordial composition that feeds galaxies in the field (e.g. Gunn & Gott 1972; Moore et al. 1996; Gnedin 1998; Hester 2006). In addition, supernova feedback from evolved stars associated with intragroup or intracluster light will directly dump metals (in particular, oxygen) into the IGM about galaxies in the highest-density environments. Along these lines, recent studies suggest that the SN Ia rate for galaxies in high-density environments such as clusters might be significantly (as much as \( \sim 3 \) times) higher than that found in the field (e.g. Mannucci et al. 2008; Carlborg et al. 2008; but see also Sharon et al. 2007). Furthermore, SNe yields may also vary with redshift (and/or environment), as suggested by recent observational and theoretical work (e.g. Howell et al. 2007; Ellis et al. 2008).

Stripping of gas from cluster members could also contribute to a higher gas-phase metallicity in extreme environments in a secondary manner. That is, ram-pressure stripping could remove the outer portion (and therefore most metal-poor segment) of a galaxy’s gas halo. Since the mixing time (assumed to be the dynamical time) for a disc galaxy is on the order of the cluster crossing time (\( \sim 2 \) Gyr), if not stripped this metal-poor gas would become effectively mixed, thereby reducing the mean metallicity within the central \( \sim 5–10 \) kpc (the region sampled by an SDSS fiber).

In the most extreme environments, pressure from the ICM could potentially resist such stripping (e.g. Babul & Rees 1992). However, hydrodynamical simulations have found that the net effect of thermal pressure and ram-pressure stripping on a cluster member still results in gas being removed from the galaxy, contributing to the ICM (Murakami & Babul 1999). On the other hand, numerical and analytical modelling of feedback in isolated galaxies shows that the ejection of metals from a galaxy’s ISM is more likely to occur in regions of lower pressure (e.g. Sihil & Tenorio-Tagle 2001; Mac Low & Ferrara 1999). Thus, thermal pressure (and its impact on the ability to drive an outflow) could account for the relative decrease in metallicity for galaxies in low-density environs.

Alternatively, the metallicity–environment relations presented in this work could also result from variations in the mass-loading factor with local galaxy density. While the mass-loading factor is, in principal, a quantity that can be directly observed (e.g. Morganti, Tadhunter & Oosterloo 2005), detailed radio measurements of a galaxy’s gas mass are required. Since we lack the required observations within the SDSS data set, we instead utilize the SDSS spectroscopic data to look for signatures of variation in outflow velocity with environment at \( z \sim 0.1 \). Although, wind speed does not necessarily provide any information about the amount of mass expelled from a galaxy, a significant variation in outflow velocity with environment could be an indication that the net accretion rate (relative to the SFR) is driving the observed metallicity–environment relations. From co-adding two sets of spectra including several hundred strongly star forming (Hz equivalent width \( > 30 \) Å), massive (\( M_\star > 10^{10} \) M\(_\odot\)) galaxies, we find no significant variation in the Na D absorption profile between extreme (low- and high-density) environments. Admittedly, our analysis is limited to the most highly star-forming galaxies, given the low resolution (\( R \sim 1800 \)) of the SDSS spectra.

Another point to consider when searching for physical sources of the strong relationship between environment and metallicity is that galaxies populating high-density regions today likely formed early in the first overdensities. Predictions of early galaxy enrichment (e.g. Schaye et al. 2003; Davé, Finlator & Oppenheimer 2006) indicate that these overdensities of gas at high \( z \) would be the most enriched environments, naturally producing a metallicity–environment relation (see also Oppenheimer & Davé 2006). Within the model of Finlator & Davé (2008), however, the gas-phase metallicity in a galaxy at \( z \sim 0.1 \) is a product of the recent (\( < 1 \) Gyr) accretion and star formation activity, rather than a result of the integrated star formation history of the galaxy (see also Dalcanton 2007). So while galaxies in high-density environments in the local Universe generally formed early in cosmic time and in the early density peaks, metallicity–environment relations imprinted at \( z \gtrsim 2 \) would not necessarily persist to the present.

Finally, within the framework of a strict closed-box chemical enrichment model (e.g. Tinsley 1977), the gas-phase metallicity depends directly on the gas-mass fraction (the ratio of the mass in gas to that in stars plus gas) and the stellar yield (the mass of metals injected into a galaxy’s ISM relative to the total mass locked up in stars and stellar remnants). Assuming that the stellar yield is constant for all galaxies, which is found to be the case for relatively massive (\( v_{\text{esc}} > 150 \) km s\(^{-1}\)) galaxies in the local Universe (Garnett 2002), then the metallicity is simply dependent (inversely) on the gas-mass fraction. In this simplified picture, star formation induced by galaxy interactions, which occur preferentially in overdense regions, could yield a correlation between higher metallicities and galaxy densities, as elevated levels of star formation in a closed-box
model will directly decrease the gas-mass fraction and therefore amplify the metallicity.

One apparent problem for this simplified model is that star formation and environment are anticorrelated locally (e.g. Gómez et al. 2003). Thus, there is no evidence that interactions are responsible for inflating the SFRs of star-forming galaxies in groups and clusters. At \( z \sim 1 \), however, an inversion or a reversal in the SFR–density relation is found (Elbaz et al. 2007; Cooper et al. 2008), such that the average SFR increases with local galaxy density. As discussed by Cooper et al. (2008), this effect is largely driven by bright, blue (star forming) galaxies in overdense regions. These systems are ideal candidates for having elevated metallicities within the closed-box paradigm. With that said, this population of bright, blue galaxies in high-density environments is not found locally, suggesting that these systems evolve into members of the red sequence by \( z \sim 0.1 \) (Cooper et al. 2006). Therefore, they would likely not be present in the SDSS sample that is examined in this work and thus not responsible for the observed correlation between metallicity and environment. In addition, the closed-box chemical evolution model is greatly oversimplified, as outflows (e.g. Tremonti, Moustakas & Diamond-Stanic 2007; van Eymeren et al. 2007; Weiner et al., in preparation) and inflows (e.g. Arribas & Collina 2002; Wong, Blitz & Bosma 2004) are found to be common among the local and distant galaxy populations.

### 7.3 Comparison to related work

As this paper was being completed, a parallel analysis of the relationship between metallicity and environment in the SDSS was presented by Mouchine, Baldry & Bamford (2007). Using a very similar data set, drawn from SDSS DR4 and employing the metallicity measurements of Tremonti et al. (2004), they find that the mass–metallicity relation depends weakly on local environment. When dividing our sample into discrete bins according to overdensity, we also find a relatively weak connection between metallicity and environment at fixed stellar mass (see Fig. 10); that is, when plotting the median mass–metallicity relation in discrete bins of overdensity, we find what appear to be only small variations among environment regimes, in close agreement with fig. 5 of Mouchine et al. (2007).

However, studying the relationships between galaxy properties and environment in this manner is far less sensitive than the techniques presented herein. Measurements of local galaxy density are inherently noisier than measures of other galaxy properties, including rest-frame colour, luminosity, stellar mass and metallicity. Thus, when dividing a sample by environment, any trends in the data set are smeared out by the significant correlation between Neighbouring bins. While Mouchine et al. (2007) conclude that gas-phase oxygen abundance is only very weakly dependent on environment at fixed stellar mass, we have presented evidence to the contrary, showing that the metallicity–environment relation is roughly equal in the strength to the colour–density relation and, moreover, that the metallicity–density relation is significantly distinct from the colour–density or stellar mass–density relations.

In contrast to our work and that of Mouchine et al. (2007), which trace galaxy environments on \( \sim 1–2 h^{-1} \) Mpc scales over the full SDSS galaxy population, the analyses of Kewley et al. (2006) and Ellison et al. (2008b) probe a far more limited range of environments, focusing on the metallicity of galaxy pairs in the local Universe. Focusing on smaller scales, they find that galaxy pairs at close (projected) separations (\( \lesssim 30 h^{-1} \) kpc) are biased towards lower metallicities. This result is attributed to inflows of metal-poor gas during the merger or interaction process, an effect is also found in simulations (Perez et al. 2006). The number of close (projected separations <100 \( h^{-1} \) kpc) pairs, however, is \( \lesssim 1 \) per cent in the SDSS sample (see also Deng et al. 2006), and thus such systems cannot be a significant contribution to the scatter in the mass–metallicity relation. While metallicity may be lower in close pairs, the dominant metallicity–environment relation moves towards higher metal enrichment in high-density environments.

### 8 SUMMARY AND CONCLUSIONS

Using the measurements of gas-phase oxygen abundance from Tremonti et al. (2004) and local galaxy environment from Cooper et al. (2008), we study the relationship between metallicity and environment in a sample of star-forming galaxies drawn from the SDSS data set. Our principal results are as follows. -

(i) We find a strong metallicity–density relation (see Fig. 3b) in the local Universe such that more metal-rich galaxies favour regions of higher galaxy overdensity. This relationship between metallicity and environment follows (with comparable or greater strength) that seen between environment and other fundamental properties such as colour, luminosity, SFR or stellar mass.

(ii) After removing the mean colour–luminosity–environment relation from the SDSS data set, we find a significant residual relationship between environment and metallicity (see Fig. 8), suggesting that metallicity has a relationship with environment separate from that observed with colour and luminosity (or with stellar mass).

(iii) The residual metallicity–environment trend is largely driven by galaxies in high-density regions such as groups and clusters, where the local environment may be responsible for impacting the feedback and/or gas accretion relative to galaxies of like stellar mass in lower density regions.

(iv) A non-negligible portion (at least 15 per cent) of the scatter in the mass–metallicity relation is correlated with local environment.

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REFERENCES

Adelberger K. L., Shapley A. E., Steidel C. C., Pettini M., Erb D. K., Reddy N. A., 2005, ApJ, 626, 636
Adelman-McCarthy J. K. et al., 2006, ApJS, 162, 38
Aguirre A., Schaye J., Hernquist L., Kay S., Springel V., Theuns T., 2005, ApJ, 620, L13
Arribas S., Colina L., 2002, ApJ, 573, 576
Babal A., Rees M. J., 1992, MNRAS, 255, 346
Balogh M. L., Schade D., Morris S. L., Yee H. K. C., Carlberg R. G., Ellington E., 1998, ApJ, 504, L75
Balogh M. et al., 2004a, MNRAS, 348, 1355
Balogh M. L., Baldry I. K., Nichol R., Miller C., Bower R., Glazebrook K., 2004b, ApJ, 615, L101
Blanton M. R., Roweis S., 2007, AJ, 133, 734
Blanton M. R. et al., 2003a, AJ, 125, 2348
Blanton M. R. et al., 2003b, ApJ, 594, 186
Blanton M. R., Eisenstein D., Hogg D. W., Schlegel D. J., Brinkmann J., 2005a, ApJ, 629, 143
Blanton M. R., Eisenstein D., Hogg D. W., Schlegel D. J., Brinkmann J., 2005b, AJ, 129, 2562
Brinchmann J., Charlot S., White S. D. M., Tremonti C., Kauffmann G., Heckman T., Brinkmann J., 2004, MNRAS, 351, 1151
Brodie J. P., Huchra J. P., 1991, ApJ, 379, 157
Brooks A. M., Governato F., Booth C. M., Willman B., Gardner J. P., Wadsley J., Stinson G., Quinn T., 2007, ApJ, 655, L17
Bruzual G., Charlot S., 2003, MNRAS, 344, 1000
Capak P., Abraham R. G., Ellis R. S., Mobasher B., Scoville N., Sheth K., Koekemoer A., 2007, ApJS, 172, 284
Carlberg R. G. et al., 2008, ApJ, 682, L25
Cavaliere A., Colafrancesco S., Menci N., 1992, ApJ, 392, 41
Chabrier G., 2003, PASP, 115, 763
Charlot S., Longhetti M., 2001, MNRAS, 323, 887
Cole S., 1991, ApJ, 367, 45
Contini T., Treyer M. A., Sullivan M., Ellis R. S., 2002, MNRAS, 330, 75
Cooper M. C., Newman J. A., Madgwick D. S., Gerke B. F., Yan R., Davis M., 2005, ApJ, 634, 833
Cooper M. C. et al., 2006, MNRAS, 370, 198
Cooper M. C. et al., 2007, MNRAS, 376, 1445
Cooper M. C. et al., 2008, MNRAS, 383, 1058
Cucciati O. et al., 2006, A&A, 458, 39
Dalcanton J. J., 2007, ApJ, 658, 941
Davé R., Finlator K., Oppenheimer B. D., 2006, MNRAS, 370, 273
Davis M., Geller M. J., 1976, ApJ, 208, 13
Dekel A., Silk J., 1986, ApJ, 303, 39
Dekel A., Woo J., 2003, MNRAS, 344, 1131
Deng X.-F., Chen Y.-Q., Wu P., Luo C.-H., He J.-Z., 2006, Chin. J. Astron. Astrophys., 6, 411
Domiano W., Gitti M., Schindler S., Kapferer W., 2004, A&A, 425, L21
Dressler A., 1980, ApJ, 236, 351
Elbaz D. et al., 2007, A&A, 468, 33
Ellis R. S. et al., 2007, ApJ, 674, 51
Ellison S. L., Patton D. R., Simard L., McConnell A. W., 2008a, ApJ, 672, L107
Tremonti C. A. et al., 2004, ApJ, 613, 898
Tremonti C. A., Moustakas J., Diamond-Stanic A. M., 2007, ApJ, 663, L77
van Eymeren J., Bomans D. J., Weis K., Dettmar R.-J., 2007, A&A, 474, 67
Veilleux S., Cecil G., Bland-Hawthorn J., 2005, ARA&A, 43, 769
Vila-Costas M. B., Edmunds M. G., 1992, MNRAS, 259, 121
Weiner B. J. et al., 2008, ApJ, submitted (arXiv:0804.4686)
Wong T., Blitz L., Bosma A., 2004, ApJ, 605, 183
York D. G. et al., 2000, AJ, 120, 1579
Zaritsky D., 1993, PASP, 105, 1006
Zaritsky D., Kennicutt R. C., Jr, Huchra J. P., 1994, ApJ, 420, 87
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