The host galaxies of strong Ca II QSO absorption systems at $z < 0.5$

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Abstract

We present new imaging and spectroscopic observations of the fields of five QSOs with very strong intervening Ca ii absorption systems at redshifts $z_{abs} < 0.5$ selected from the Sloan Digital Sky Survey. Recent studies of these very rare absorbers indicate that they may be related to damped Lyman alpha systems (DLAs). In all five cases we identify a galaxy at the redshift of the Ca ii system with impact parameters up to $\sim 24 \text{ kpc}$. In four out of five cases the galaxies are luminous ($L \approx L^*$), metal-rich ($Z \approx Z_\odot$), massive (velocity dispersion $\sigma \approx 100 \text{ km s}^{-1}$) spirals. Their star formation rates, deduced from H$\alpha$ emission, are high, in the range $SFR = 0.3 - 30 \text{ M}_\odot \text{ yr}^{-1}$. In our analysis, we paid particular attention to correcting the observed emission line fluxes for stellar absorption and dust extinction. We show that these effects are important for a correct SFR estimate; their neglect in previous low-$z$ studies of DLA-selected galaxies has probably led to an underestimate of the star formation activity in at least some DLA hosts. We discuss possible links between Ca ii-selected galaxies and DLAs and outline future observations which will help clarify the relationship between these different classes of QSO absorbers.

Key words: galaxies: abundances – galaxies: ISM – quasars: absorption lines

1 INTRODUCTION

Following star formation throughout the Universe’s history is key to understanding how galaxies have evolved. A wide variety of methods have been used to probe galaxies and their star formation activity over the cosmic ages. At high redshifts, most of the information at our disposal comes on the one hand from direct observations of star-forming galaxies over most of the electromagnetic spectrum – from X-ray to radio wavelengths – and, on the other, from indirect, but more precise, studies of the interstellar absorption lines produced by intervening galaxies in the spectra of background quasars (QSOs). These two techniques should be complementary, and yet it has proved difficult until recently to bring their respective results together into one comprehensive picture. The aim of this paper is to bridge this gap by presenting direct imaging and spectroscopic observations of galaxies originally selected via their absorption characteristics.

The class of QSO absorption-line systems (QALs) which has been studied most extensively in this respect are the damped Lyman-$\alpha$ systems (DLAs), defined by neutral hydrogen column densities $N_{\text{HI}} \geq 2.0 \times 10^{20} \text{ cm}^{-2}$. At the upper of the column density distribution of QALs, DLAs should account for most of the neutral gas in the Universe at $z \sim 3$ and have thus long been regarded as the likely reservoirs of gas available for star formation (Wolfe, Gawiser & Prochaska 2005). However, this potential for star formation is apparently yet to be realized by most galaxies identified as DLAs. Attempts to measure the star-formation rate of DLA hosts – whether through direct imaging (Wolfe & Chen 2006; Honkins, Rao & Turnshek 2005) and spectroscopic detection (Kulkarni et al. 2004, and references therein), or through indirect arguments based on the inferred heating rate (Wolfe, Prochaska & Gawiser 2003) – have generally returned relatively modest values, lower than expected from a straightforward application of the Schmidt law to their surface mass densities of H1. Similarly, the metal content of most DLAs is less than 1/10 solar at most redshifts (Akerman et al. 2003; Kulkarni et al. 2005), lower than that of the disk of the Milky Way over most of its past history (Pettini 2006).

These characteristics are in stark contrast with those of galaxies detected directly through their starlight at similar redshifts in surveys such as those of Steidel et al. (2003, 2004). Such ‘Lyman break’, or more generally UV-bright, galaxies have star-formation rates $SFR \approx 10 - 100 \text{ M}_\odot \text{ yr}^{-1}$ (e.g. Reddy et al. 2005, 2006) and have already reached near-solar metallicities at $z = 2 - 3$ (Pettini et al. 2001, Erb et al. 2006).

If we are to reconcile these apparently contradictory results, it is essential to image the DLA absorbers and measure the metallicities of their star-forming regions, for comparison with the values measured in the cold gas which evidently dominates the absorption cross-section. Clearly, such efforts should focus first on DLAs at...
$z \lesssim 1$, where both imaging and spectroscopy are easier to perform than at higher redshifts. Once the connection between galaxies and DLAs has been clarified at $z \lesssim 1$, it may be easier to interpret the data at higher redshifts. While there have been a few attempts in this general direction (e.g. Ellison, Malen-Ornelas & Sawicki 2003; Bowen et al. 2005; Chen, Kennicutt & Rauch 2005; Zwaan et al. 2005), the body of relevant data is still very thin, mainly because surveys of DLAs at $z < 1$ require ultraviolet spectroscopy from space which is currently unavailable until the next servicing mission installs the Cosmic Origin Spectrograph on the Hubble Space telescope (HST).

Until then we have to rely on methods other than the direct detection of a damped Lyman-$\alpha$ absorption line to identify DLAs at $z \lesssim 1$. We are greatly aided in such endeavours by the unprecedented statistical power of the Sloan Digital Sky Survey (SDSS). In a recent development, Wild & Hewett (2005) identified a sample of rare QALs characterized by strong Ca $\alpha\lambda\lambda3934,3969$ absorption. Wild & Hewett (2005) showed that Ca $\alpha$ systems selected to have a rest-frame equivalent width of the stronger member of the doublet $W_0^{3934} \gtrsim 0.2$ Å are likely to have high values of $N$(HI); they may well be a subclass of DLAs (Wild, Hewett & Pettini 2006, henceforth WHP06). However, their connection to the Ly$\alpha$-selected DLAs has yet to be fully clarified. WHP06 also found that the $z \sim 1$ strong Ca $\alpha$ absorbers have higher average dust extinction than most DLAs [$E(B-V) \sim 0.1$ mag] and average dust-to-metals ratio as high or higher than the Milky Way. Their number density was also found to be $\sim 20$–$30$ per cent that of the DLA population at the same redshift. From recent $K$-band imaging of strong Ca $\alpha$ absorbers, also at $z \sim 1$, Hewett & Wild (2007) find a mean impact parameter of 24 kpc with a filling factor of only $\sim 10$ per cent for their sample. They also find that the luminosity dependence of the Ca $\alpha$ absorber cross-section [$\sigma \propto (L/L_\odot)^{0.7}$] is stronger than the dependence established for strong Mg $\alpha$ absorbers.

From the extensive body of work carried out on Ca $\alpha$ absorption in the Galactic interstellar medium (ISM) over the last 50 years, we do know that, locally at least, the Ca $\alpha$ lines are seldom very strong because: (i) with an ionization potential close to, but lower than, that of H$\alpha$ (11.9 eV compared to 13.6 eV), Ca $\alpha$ may not be the major ionization stage of Ca in H$\alpha$ regions where a significant fraction of Ca may be doubly ionized; and (ii) more importantly, Ca is among the most depleted elements in the gaseous phase of the ISM, being readily incorporated into dust grains (e.g. Savage & Sembach 1996). Thus, it is conceivable that strong Ca $\alpha$ absorption may preferentially arise in environments where some fraction of the grains has been destroyed – and the proportion of gaseous Ca consequently enhanced by a large factor – by supernova-driven shocks associated with star-formation activity (Routly & Spitzer 1952).

Partly to test this hypothesis, Wild, Hewett & Pettini (2007, henceforth WHP07) stacked the SDSS spectra of QSOs with strong Ca $\alpha$ systems to search for [O $\alpha$] emission from the absorbing galaxies. They found that the population as a whole exhibits only modest levels of in-situ star formation activity, with an average rate $\langle$SFR$\rangle = 0.11 - 0.48$ M$_\odot$ yr$^{-1}$. In order to place this result in context, establish the nature of the strong Ca $\alpha$ absorbers, and clarify their relationship, if any, to the DLA population, we have begun a programme of deep imaging and spectroscopy targeting initially the fields of SDSS QSOs with strong Ca $\alpha$ absorption at $z_{abs} \lesssim 0.5$. In this paper we report the first results of this survey for five fields: in each case we have detected galaxies at the redshift of the absorber and, unlike previous studies, we find them to be luminous, actively star-forming, and rich in metals and dust. While this may be partly due to the bias of our first observations in favour of easily recognized, and therefore luminous, galaxies, these initial results show that Ca $\alpha$ absorbers should play an important role in improving our understanding of the general absorber population in the future.

The paper is structured as follows. In Section 2 we review our sample selection, describe the observations, which were conducted with the FORS2 spectrograph on the Very Large Telescope (VLT) of the European Southern Observatory, and discuss the subsequent data reduction steps. We pay particular attention to fitting the underlying stellar absorption along the Balmer series and to dust extinction corrections. In Section 3 we describe the general properties of our Ca $\alpha$-selected galaxies. In Section 4 we deduce star formation rates and oxygen abundances using well established emission line diagnostics and compare them with analogous measures from the literature for the hosts of Ly$\alpha$-selected DLAs. Finally, Sections 5 and 6 present our discussion and conclusions, respectively.

Throughout this paper we adopt the currently favoured values of the cosmological parameters $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_{\Lambda,0} = 0.3$ and $\Omega_{\text{M},0} = 0.7$. Wavelengths are quoted in a vacuum, heliocentric frame of reference.

## 2 SAMPLE SELECTION, OBSERVATIONS, DATA REDUCTION AND ANALYSIS

In addition to describing the observations, data reduction and analysis, we pay particular note to the systematic effects involved in our analysis. This includes fitting the underlying stellar absorption along the Balmer series and dust reddening corrections.

### 2.1 Selection

Absorbers were identified by searching for features with rest frame equivalent width, $W_0^{3934} \gtrsim 0.2$ Å at $4.7$σ significance in the sample of all 49409 SDSS DR3 QSOs with $z_{em} \geqslant 0.05$, classified by having ‘specClass’ = 3 or 4 in the SDSS. It was also required that the Ca $\alpha\lambda3969$ line had a significance $> 1$σ. Detections were required to lie outside the Ly$\alpha$ forest and if two detections were separated by less than 500 km s$^{-1}$ in redshift space they were classified as a single absorption system. Absorber redshifts were measured using Gaussian profile fits. For a candidate absorber to be confirmed as real it also had to show Mg $\alpha$ absorption with $> 6$σ significance at $z_{abs} \geqslant 0.37$ or, for $z_{abs} < 0.37$, Na $\alpha$ absorption at $> 1$σ since the wavelengths of the Mg $\alpha$ lines then lie outside the SDSS spectral range. The sample was restricted to $z_{abs} < 0.5$ to allow the H$\alpha$ emission line to be observed in the optical and to allow easier identification of host galaxies from SDSS imaging. Finally, the sample spectra were visually inspected, to reject absorbers which did not look convincing. This left a sample of 40 absorbers. Despite these checks there is a possibility that up to ten per cent of the absorbers in the sample could be spurious due to the difficulty of identifying the relatively weak Ca $\alpha$ features, particularly at low-$z$ when stellar photospheric Ca $\alpha$ H&K lines are often detected. Photospheric Ca $\alpha$ H&K detections can usually be eliminated by their very strong Ca $\alpha$ equivalent widths combined with presence of other strong photospheric absorption features such as the Na $\alpha$, Fe $\alpha$ and Mg $\alpha$ lines. However, some Ca $\alpha$ absorption was subsequently found to be of

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1 These are the familiar Ca $\alpha$ K & H lines first identified in the solar spectrum and subsequently studied extensively in the interstellar medium of the Milky Way.
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2.3 Data reduction

The FORS2 data were reduced using standard \texttt{iraf}\footnote{\texttt{iraf} is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy Inc. (AURA) under cooperative agreement with the National Science Foundation.} packages, except for the \texttt{apextract} package which we modified as detailed below. The 2D spectral frames were bias subtracted, flat fielded and wavelength calibrated. Cosmic rays were then identified via Laplacian edge detection using \texttt{L.A. COSMIC}\footnote{Available at \url{http://www.ast.cam.ac.uk/~mim/UVES_popler.html}} (van Dokkum 2001). The modified version of \texttt{apextract} was then used to extract the 1D spectra.

We found that the standard \texttt{iraf} optimal extraction routine often created inappropriate weighting profiles as our galaxy sources are extended, rather than point-like. Therefore we added the option of pure variance weighting of the data during extraction (i.e. using a uniform spatial profile for weighting). Furthermore, we wished to improve upon the cosmic ray identification and removal in \texttt{iraf}. Therefore, we added the option of inputting a predetermined cosmic ray mask into the extraction procedure. During extraction \texttt{iraf} calculates the variance-weighted mean flux in the spatial direction for each spectral pixel. We simply allowed pixels which were pre-identified as cosmic rays to be masked during this process.

Finally, the 1D spectra were flux calibrated and corrected for telluric absorption using observations of standard stars. Individual spectra were vacuum and heliocentric corrected and combined using the software package, \texttt{UVES POPLER}\footnote{During this process, all data were rebinned into the same linear wavelength scale. Each exposure is also scaled up to the flux level of the highest signal-to-noise ratio (S/N) exposure using a single scale factor in each case. This ensures that, even for exposures which were affected by cloud, we should achieve optimal flux calibration.}. During this process, all data were rebinned into the same linear wavelength scale. Each exposure is scaled up to the flux level of the highest signal-to-noise ratio (S/N) exposure using a single scale factor in each case. This ensures that, even for exposures which were affected by cloud, we should achieve optimal flux calibration.

Between sets of exposures taken in photometric conditions we found differences of less than five per cent in absolute flux calibration. Good quality spectrophotometric standards and use of the ADC ensure that relative flux calibration error is minimal – the red and blue flux distribution of individual exposures in each target show that relative errors are up to four per cent. The SDSS data utilized has accurate spectrophotometric calibration (Tremonti et al. 2004), thus flux calibration errors are not the dominant source of error in our sample (see Section 2.7).

Emission lines were corrected for Galactic extinction using the Milky Way (MW) dust map created by Schlegel, Finkbeiner & Davis (1998) and the reddening curve given by Cardelli et al. (1989).

2.4 Aperture corrections

Geometric corrections are required for each galaxy to account for the fact that the slit used for spectroscopy did not include all the star-forming light from the galaxy. To calculate the corrections for our sample we assume that our \(r\)-band acquisition imaging traces the H\(\alpha\) and [O\(\text{iii}\)] line flux. The resulting corrections, derived by taking the ratio of total galaxy \(r\)-band flux to that in the slit are factors between 1 and 2.2. Individual corrections are given in Table 9 with the resulting corrected SFRs in Section 4.3. We utilize these geometric corrections where appropriate. In particular we use uncorrected SFRs when comparing our work to that conducted on...
Table 1. Observed objects, redshifts and Ca ii equivalent widths. The available galaxy spectral data sets are also noted (†FORS2, ∗SDSS)

| Object        | SDSS name            | z_{abs} | z_{QSO} | W_{3934}^{\text{SDSS}} / Å | W_{3934}^{\text{FORS2}} / Å |
|---------------|----------------------|---------|---------|----------------------------|-----------------------------|
| J0019−1053†   | SDSSJ001946.99−105313.3 | 0.347   | 1.518   | 0.6 ± 0.1                  | 0.47 ± 0.03                 |
| J0912+5939†   | SDSSJ091204.90+593957.7 | 0.212   | 0.773   | 0.52 ± 0.09                | −                           |
| J1118−0021†   | SDSSJ111850.13−002100.8 | 0.132   | 1.025   | 0.62 ± 0.15                | 0.79 ± 0.03                 |
| J1219−0043†   | SDSSJ121911.23−004345.5 | 0.448   | 2.293   | 0.57 ± 0.08                | −                           |
| J2246+1310†   | SDSSJ224630.63+131048.5 | 0.395   | 1.593   | 0.9 ± 0.2                  | 0.59 ± 0.02                 |

Figure 1. Summary of the data available for J0019−1053. The top left panel shows the stacked r-band FORS2 acquisition image. The solid red lines shows the FORS2 slit positioning, whilst the dashed red line shows the SDSS fibre placement. Image scale and orientation are indicated in the bottom left and right hand corners, respectively. The top right panel shows the Ca ii line detection in the SDSS QSO spectrum. We also plot the more significant FORS2 QSO Ca ii line detection (when available). For clarity, the FORS2 spectrum flux scale is offset from that of the SDSS spectrum by four arbitrary flux units. The solid black line shows the observed flux, whilst the solid green and dashed red lines show the 41 pixel median filter continuum and error array, respectively. The positions of the Ca ii λλ3934,3969 lines are indicated by the dotted red lines. The bottom panels show portions of the FORS2 galaxy spectrum around the emission lines labeled in the top left corner of each plot. The solid black line indicates the observed flux after galaxy continuum subtraction. The solid green line shows the fitted Gaussian profiles, whilst the dashed red line shows the error array in each case. In the case of Hβ the dotted green line shows the base of the stellar absorption fit. Wavelength scales are in the observed frame.

Figure 2. Summary of the data available for J0912+5939. See Fig. 1 for description of each panel. Note that no FORS2 galaxy spectra were taken so we present instead the SDSS r-band image. The galaxy spectrum is observed through the same fibre as the QSO. Note also that no absorption or emission fit is possible to the Hβ line; see Section 2.6. The SDSS MJD, fibre and plate numbers for this QSO are 51907, 459 and 0484, respectively.
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Figure 3. Summary of the data available for J1118−0021. See Fig. 1 for description of each panel.

Figure 4. Summary of the data available for J1219−0043. See Fig. 1 for description of each panel. Note that the Hβ absorption was fitted by eye in this case; see Section 2.5.

Figure 5. Summary of the data available for J2246+1310. See Fig. 1 for description of each panel. For clarity, the FORS2 spectrum flux scale is offset from that of the SDSS spectrum by three arbitrary flux units.
2.5 General spectral analysis and removal of underlying stellar absorption

The data were analysed using a combination of the Starlink package, dpso, and ngausfit from the IRAF STSDAS package. The resolution of the data allowed the H\(_\alpha\) and [N\textsc{ii}] emission lines to be resolved and accurate fitting of the stellar absorption around H\(_\beta\). Continua were fitted interactively, using a spline interpolation, and subtracted from the total flux. The emission lines were fitted with Gaussian profiles to calculate total line flux.

There can be a large amount of uncertainty in the fitting of stellar absorption along the Balmer series (e.g. [Diaz] 1988; González Delgado et al. 1999); this in turn can cause a significant uncertainty in line measurements and hence in the estimated dust reddening from the Balmer decrement. We therefore compared two different methods for fitting the H\(_\beta\) line, one fitting the emission and absorption simultaneously using Gaussian profiles, the other using a Gaussian profile in emission whilst the absorption was spline fitted by eye. The W0 of the absorption is smaller when fitted by eye, resulting in a ten per cent systematic difference in the integrated line fluxes. The Gaussian absorption fits better reflect the shape of the stellar absorption derived from stellar synthesis models, built up from individual stars, than the by-eye spline fits hence we adopted those where possible. J1219−0043 is the exception to this, which was spline fitted by eye because the results from nGAUSFIT were very sensitive to the initial conditions for the fit.

In most analyses in the literature the effects of stellar absorption on H\(_\alpha\) are neglected because the emission equivalent width is much greater than that of absorption. However, H\(_\alpha\) absorption was significant for some of our objects. Note that H\(_\alpha\) stellar absorption cannot be corrected directly because the [N\textsc{ii}] lines mask the absorption at the resolution of our data. We therefore used the following prescription to correct the H\(_\alpha\) line for stellar absorption. For normal star-forming spiral galaxies the following relationship between W0 of stellar absorption at H\(_\beta\) and H\(_\alpha\) applies (J. Moustakas, private communication).

\[
W^\text{abs}_0 (H\alpha) = 0.23 + 0.59 \times W^\text{abs}_0 (H\beta)
\]

(1)

This relationship is based on a linear bisector fit to the measured H\(_\alpha\) and H\(_\beta\) stellar absorption from stellar synthesis modeling of the galaxies in the Moustakas, Kennicutt & Tremonti (2006) and Nearby Field Galaxy Survey (NFGS, Jansen et al. 2006) samples. The 1σ dispersion in the relationship is 0.11 dex (0.09 dex, rejecting the ten 3σ outliers from the total sample of 407).

We then use the reasonable assumption that the velocity structures (of both emission and absorption) at H\(_\beta\) and H\(_\alpha\) are the same. This allows us to correct the H\(_\alpha\) line flux for stellar absorption via

\[
F^\text{absor}_0 (H\alpha) = \frac{W^\text{em}_0 (H\alpha)}{W^\text{em}_0 (H\beta)} F^\text{abs}_0 (H\beta),
\]

(2)

where W^\text{em}_0 (H\alpha) is the equivalent width derived in equation (1) and W^\text{em}_0 (H\beta) is the measured rest-frame equivalent width of the H\(_\beta\) emission line. \(f\) is a correction factor which varies between spectra. It represents the fraction of the total stellar absorption measured when calculating the equivalent width across the emission profile, rather than across both the emission profile and broader absorption profile. This is necessary because one can not measure W^\text{abs}_0 (H\beta) across the same width in wavelength space as W^\text{abs}_0 (H\alpha), due to the presence of the [N\textsc{ii}] lines (refer to H\(_\alpha\) and H\(_\beta\) spectra in Figs. [1][5]). However, it is straightforward to measure \(f\) directly from the H\(_\alpha\) line. Table 3 gives the measured H\(_\beta\) and H\(_\alpha\) stellar absorption equivalent widths and the measured correction factor, \(f\). Noise in their data precluded this analysis on J0912+5939 and J1219−0043, thus we do not correct their H\(_\alpha\) line fluxes and quote results based on them as lower limits. It is clear that the corrections are not inappropriate given that our different metallicity determinations all agree within 0.3 dex (see Section 4.2).

Extracted spectra of the emission line regions with fits used to calculate integrated line fluxes can be found in Figs. [1][5] and Table 2 lists measured emission line fluxes.

Active Galactic Nuclei (AGN) contamination can be a significant problem in galaxy emission line studies. In Fig. 3 we plot each galaxy in [N\textsc{ii}]/H\(_\alpha\)–[O\textsc{iii}]/H\(_\beta\) space, the AGN diagnostic developed by Baldwin, Phillips & Terlevich (1981) and Veilleux & Osterbrock (1987). The harder radiation in AGN compared to star-forming regions cause an enhanced [O\textsc{iii}]/H\(_\beta\) ratio with respect to [N\textsc{ii}]/H\(_\alpha\). The loci derived by Kewley et al. (2001) and measured by Kauffmann et al. (2003) define the boundary beyond which AGN contamination is significant. AGN contamination is therefore not significant for our galaxies.

Table 2. A summary of the observations taken at the ESO VLT using the FORS2 long slit spectrograph.

| Object | Grism | Filter | R | Exposure time / s |
|--------|-------|--------|---|-------------------|
| J0019−1053 | 300V+20 | GG435+81 | 440 | 5200 |
| J1118−0021 | 600B+12 | none | 780 | 3600 |
| J1219−0043 | 300V+20 | GG435+81 | 440 | 6540 |
| J2246+1310 | 300V+20 | GG435+81 | 440 | 6400 |
| J0021+4109 | 600B+12 | none | 780 | 3600 |

Table 3. The stellar absorption as measured at H\(_\beta\) and derived for H\(_\alpha\) for our sample of galaxies. The correction factor, \(f\), is required in equation (2) to correct for stellar absorption at H\(_\alpha\). Also tabulated is the measured emission line equivalent width at H\(_\alpha\).

| Object | W^\text{abs}_0 (H\beta) / Å | W^\text{abs}_0 (H\alpha) / Å | f | W^\text{em}_0 (H\alpha) / Å |
|--------|--------------------------|-----------------------------|---|--------------------------|
| J0019−1053 | 7 ± 1 | 4.2 ± 0.7 | 0.62 | 58.77 ± 0.01 |
| J1118−0021 | 4.6 ± 0.8 | 2.9 ± 0.5 | 0.31 | 14.825 ± 0.002 |
| J2246+1310 | 5 ± 1 | 3.2 ± 0.8 | 0.31 | 28.81 ± 0.02 |

2.6 Dust extinction of emission line flux

Dust extinction corrections are essential, particularly at shorter wavelengths where attenuation due to dust is higher. This is demonstrated in Section 4.3. For simplicity, uncorrected flux values were used for those metallicity (and AGN) indicators which are robust against relative differences in flux calibration, otherwise extinction corrected flux values were used.

We estimate the galaxy extinction using the Balmer decrement between H\(_\alpha\) and H\(_\beta\). We assume an intrinsic Balmer decrement of 2.85 (for case B recombination at \(T = 10^5\) K and \(n_e \sim 10^4\) cm\(^{-3}\); Osterbrock 1989). This is representative of H\(_\alpha\) regions. The colour excess can then be defined.
we are interested in the MW, Large Magellanic and Small Magellanic Clouds (LMC, SMC, respectively) have similar extinction curves (Cardelli et al. 1989; Misselt, Clayton & Gordon 1999; Gordon & Clayton 1998), differing no more than ten per cent at most. As is shown in Section 3, our galaxies more closely resemble the MW than the LMC or SMC, hence we choose to use a MW attenuation curve for the rest of our analysis. Aside from the choice of extinction curve, the error in $E(B-V)$ is dominated by the systematics involved in fitting stellar absorption (see Section 2.5).

For J0912+5939 the Hβ line is coincident with Galactic Na i absorption while for J1219–0043 the Hβ absorption line fit was uncertain (see Section 2.5). Therefore, we do not estimate $E(B-V)$ for these lines of sight. As can be seen from Table 4 the derived extinctions for our sample are above the average value observed in normal star-forming galaxies at low redshift ($E(B-V)$ ~ 0.36 mag), although they lie within the distribution of values from such galaxies (Kennicutt 1992; Moustakas et al. 2006).

2.7 Systematic effects and error budget

It is generally the case that systematic sources of error dominate the error budget for both SFRs and metallicities derived empirically from galaxy emission lines. As highlighted previously, the major sources of systematic error are flux calibration (see Section 2.3), slit losses (see Section 2.4), fitting of stellar absorption along the Balmer series (see Section 2.5) and extinction corrections (see Section 2.6). These are not independent of each other. However, the most significant source of error was the fitting of the stellar absorption. This corresponds to a maximum of 0.1 dex variation in metallicities and ten per cent variation in SFRs. The effect on metallicity is small for two reasons. Firstly, the metallicity measurements rely on flux ratios of lines close in wavelength (R23 metallicities being affected because of the larger separation between [O ii] and [O iii]). Secondly, the empirically calibrated metallicity indicators have only a shallow dependence on the relevant line ratios. Due to the variation in calibration between different metallicity indicators, the derived metallicities for any single galaxy can vary by up to 0.3 dex. This indicator calibration variation therefore dominates the error in our derived metallicities.

3 GENERAL PROPERTIES OF OUR Ca ii-SELECTED GALAXIES

From FORS2 acquisition and SDSS images we measured the galaxy properties collected in Table 5. They include measurements of their r-band magnitudes, rest-frame B, band luminosities, QSO–galaxy impact parameters, morphological classification (via spec-

Table 4. Measured galaxy integrated line fluxes. Galactic dust extinctions and integrated galaxy dust extinctions for each target. We note that the systematic errors in $E(B-V)_\text{gal}$ are approximately an order of magnitude larger than the quoted random errors and are dominated by the estimate of the stellar absorption at Hβ and Hα; see text. Upper limits are quoted at 3σ significance.

| Object     | $z_{\text{obs}}$ | Hα | [N ii] λ6585 | [N ii] λ6549 | Hβ  | [O iii] λ5008 | [O iii] λ4960 | [O iii] λ4377 | $E(B-V)_\text{gal}$ | $E(B-V)_\text{gal}$ |
|------------|-----------------|----|-------------|-------------|-----|-------------|-------------|-------------|-------------------|-------------------|
| J0019–1053 | 0.347           | 2230 ± 40 | 870 ± 30    | 280 ± 30    | 420 ± 50 | 100 ± 7     | 37 ± 9      | 460 ± 20    | 0.033 ± 0.001     | 0.55 ± 0.04       |
| J0912+5939 | 0.212           | 320 ± 40  | <110        | <40         | <40   | 200 ± 30    | 60 ± 20     | 230 ± 40    | 0.042 ± 0.001     | –                 |
| J1118–0021 | 0.132           | 1730 ± 20 | 730 ± 20    | 250 ± 20    | 300 ± 30 | 80 ± 20     | 28          | 390 ± 30    | 0.050 ± 0.003     | 0.61 ± 0.04       |
| J1219–0043 | 0.448           | 310 ± 20  | 130 ± 20    | 60 ± 20     | 83 ± 8  | 16 ± 6      | <5          | 101 ± 8     | 0.032 ± 0.001     | –                 |
| J2246+1310 | 0.395           | 610 ± 10  | 239 ± 9     | 43 ± 9      | 131 ± 5 | 58 ± 6      | 21 ± 6      | 213 ± 7     | 0.051 ± 0.002     | 0.42 ± 0.02       |

Figure 6. [O iii]/Hβ vs. [N ii]/Hα diagnostic diagram. The galaxies considered in this work are shown with large red circles. The small cyan circles are galaxies from the KISS survey (Salzer et al. 2005) and the small black dots are local starburst galaxies from (Kewley et al. 2001). The dashed line shows the locus of points which (Kewley et al. 2001) consider to be the theoretical limit for starbursts, in the sense that galaxies without an AGN component should fall below and to the left of this line. The dotted line is an empirical determination by (Kauffmann et al. 2003) of the same limit. It is evident from their [N ii]/Hα and [O iii]/Hβ ratios that AGN contamination is unlikely to be significant in our galaxies.

$E(B-V) \equiv -2.5 \log \left( \frac{\text{Hα}/Hβ}_\text{int} - \log \left( \frac{\text{Hα}/Hβ}_\text{obs} \right) \right) / k(Hα) - k(Hβ)$,

where (Hα/Hβ)$_\text{obs}$ is the Balmer decrement observed after correction for stellar absorption, (Hα/Hβ)$_\text{int}$ is the intrinsic Balmer decrement and $k(λ)$ is the extinction curve. $k(Hα)$ and $k(Hβ)$ are the values of $k(λ)$ at 6564 and 4862 Å, respectively from Cardelli, Clayton & Mathis (1989). The extinction curve and this $E(B-V)$ are used to correct all the measured line using the following expression,

$\log F_{\text{em}}(λ) = 0.4 k(λ) E(B-V) \log F_{\text{obs}}(λ)$,

where $F_{\text{em}}(λ)$ is the extinction corrected integrated line flux and $F_{\text{obs}}(λ)$ is the observed integrated line flux. In the case of Balmer series lines, this observed flux has been corrected for stellar absorption as discussed in Section 2.5. Over the wavelength range...
the Model magnitude will consist of QSO. The PSF profile will predominantly consist of the QSO, whereas we calculated its magnitude by taking the distance modulus, $L_{B}^{*}$, and $L_{B}$ (both galaxy and QSO respectively). Most of our galaxies were classified photometrically in the SDSS, and therefore have SDSS $ugriz$ magnitudes (Maddox & Hewett 2006) to identify resolvable galaxy components.

### 3.1 Galaxy luminosities

Most of our galaxies were classified photometrically in the SDSS and therefore have SDSS $ugriz$ Model magnitudes and errors (the Model profile is the De Vaucouleurs or exponential profile, whichever fit has the lower $\chi^2$). J0912+5939 was too close to the QSO sight-line for it to be detected independently in the SDSS. Instead we calculated its magnitude by taking the difference between its QSO PSF and Model magnitude. The assumption here is that the PSF profile will predominantly consist of the QSO, whereas the Model magnitude will consist of QSO + galaxy. In practice some galaxy light will contribute to the PSF magnitude as well, but this contamination is not significant unless the galaxy is resolved (e.g. Schneider et al. 2003). Galaxy $r$-band magnitudes are listed in Table 5.

Absolute $B_{j}$ magnitudes (Maddox & Hewett 2006) are derived from $r$-band magnitudes, via the best fitting Coleman, Wu & Weedman (1981) spectral energy distribution (SED). The best fitting CWB SED is selected as that which has the smallest $\chi^2$ when fitted to the SDSS $ugriz$ extinction corrected, AB magnitudes. The best fitting models are listed in Table 5. The best-fitting SED is then used to calculate the appropriate K-correction, $K(z)$, for the $r$-band distance modulus, $m - M = 5 \log(D_{L}) - 5 + K(z)$, which results in an absolute $r$-band magnitude. Here $D_{L}$ is the luminosity distance to the galaxy in parsecs. The $B_{j} - r$ colour at $z = 0$ for the best fit SED is then used to convert to $B_{j}$ magnitudes. We note that the required K-corrections are small (~0.3 mag) because the rest frame $B_{j}$-band is similar to the SDSS $r$-band at the redshifts of our galaxies. AB magnitudes are converted to standard Vega magnitudes using the tabulation of Hewett et al. (2006), adopting a +0.03 V mag for Vega. The absolute $B_{j}$ magnitude of an $L^*$ galaxy in our cosmology is $M_{B}^* = -20.43$ mag (Norberg et al. 2002). There is some evidence for an evolution of $L^*$ with redshift, though the exact form of this evolution is still under debate. We therefore choose to evolve $L^*$ with redshift using the simple prescription of Ilbert et al. (2005), $M_{B}^*(z) = M_{B}^*(0) - z$, which is reasonable at low-$z$ for the small redshift range we sample. Choosing an evolving model for $L^*$ does not affect the conclusions we draw from the measured luminosities. This leads to a galaxy luminosity via the following simple relationship,

$$\log(L/L^*) = \log (F/F^*) = -0.4 \left(M_{B}^* - M_{B}^*(z_{gal})\right).$$

(5)

Formal errors on the SDSS magnitudes were propagated throughout. No error from SED selection was folded into the analysis. The choice of SED does not significantly affect the derived luminosities because the variation in magnitude resulting from different SED fits is of order the statistical error. No intrinsic error was assumed for the AB-to-Vega magnitude conversion or for $M_{B}^*$. Note that most of our galaxy have luminosities close to $L^*$ (see Table 5). It is likely that we have biased our sample to high luminosities by observing galaxies we could easily identify in SDSS images (see Section 5).

### 3.2 QSO–galaxy impact parameters

For most objects, where both galaxy and QSO were identified as distinct objects in the SDSS, we measure the QSO–galaxy impact parameters by taking the difference between their J2000 coordinates, assuming an error between co-ordinates of 01 2, the typical accuracy of relative object positions in the SDSS. J0912+5939 is not independently identified in the SDSS and we have no, higher resolution, FORS2 images either. Given that we know the target is relatively bright, based on galaxy luminosity and emission line strength, we adopt a conservative upper limit to the impact parameter of less than the SDSS fibre radius, 11.5.

### 3.3 Galaxy velocity dispersions

It is straight-forward to measure the line-widths, $\sigma_{\text{obs}}$, of our fitted Hα profiles for each galaxy. For $\sigma_{\text{obs}} > \sigma_{\text{ins}}$, the instrumental profile width, direct application of the convolution theorem, assuming Gaussian profiles, gives us a reliable measure of the galaxy velocity dispersion,

$$\sigma_{\text{gal}}^2 = \sigma_{\text{obs}}^2 - \sigma_{\text{ins}}^2 - \sigma_{\text{th}}^2.$$  

(6)

where $\sigma_{\text{th}}$ is the thermal broadening of the Hα line ($= \sqrt{2kT/m} = 9 \text{ km s}^{-1}$ at $10^4 K$). The instrumental profile widths, $\sigma_{\text{ins}}$, for each setting were measured from the extracted wavelength calibration arcs and the errors were derived from the standard deviation from the mean of many arc lines: $\sigma_{\text{obs}} = 1.9 \pm 0.1 \text{ Å}$, $\sigma_{\text{th}} = 4.3 \pm 0.2 \text{ Å}$, $\sigma_{02500} = 2.19 \pm 0.04 \text{ Å}$, $\sigma_{05000} = 2.11 \pm 0.04 \text{ Å}$. For $\sigma_{\text{obs}} > \sigma_{\text{ins}}$ the deconvolution is unlikely to be meaningful at the S/N of our spectra, so we do not quote a result in this case. The results are collected in Table 5.

To derive rotational velocities or dynamical masses from the measured Hα line velocity dispersions requires many assumptions.

### Table 5. Measured SDSS $r$-band magnitudes, $B_{j}$ galaxy luminosities, QSO impact parameters, Hα line widths, best fitting CWB SEDs and morphological classifications.

| Object | $z_{\text{abs}}$ | $r$/mag | $L/L^* \left(B_j\right)$ | $b''$ | $b$/kpc | $\sigma$(Hα)/km s$^{-1}$ | SED | Hubble Type |
|--------|-----------------|---------|-------------------------|-------|---------|------------------------|-----|-------------|
| J0019–1053 | 0.347 | 20.21 ± 0.03 | 0.89 ± 0.03 | 3.5 ± 0.2 | 17 ± 1 | – | Scd | – |
| J0912+5939 | 0.212 | 21.2 ± 0.4 | 0.13 ± 0.05 | $\lesssim 1.5$ | < 5 | 100 ± 20 | Im | – |
| J1118–0021 | 0.132 | 17.22 ± 0.01 | 1.75 ± 0.02 | 9.9 ± 0.2 | 23 ± 0.5 | – | Sbc | S0 |
| J1219–0043 | 0.448 | 21.2 ± 0.1 | 0.68 ± 0.07 | 1.3 ± 0.2 | 7 ± 1 | 100 ± 40 | Sbc | – |
| J2246+1310 | 0.395 | 20.45 ± 0.05 | 1.01 ± 0.05 | 1.2 ± 0.2 | 6 ± 1 | 98 ± 9 | Scd | – |
this paper. However, for galaxies at \( z \approx 0.25 \) (e.g. Erb et al. 2006) and such an analysis is beyond the scope of this paper. Moreover, rotational velocity, \( v \), is important in identifying such DLAs with- out difficulties in determining their source of 

\[
\frac{v}{(8 	ext{ kpc})} \approx 25 \text{ Rix et al. (1997) show that on average, rotational velocity, } v, \text{ is important in identifying such DLAs with-
\]

cout such DLAs without such difficulties in determining their source of extinction. Hence, when comparing our results with others in the literature (see Section 4.1),

Prior to presenting our new results, we review the results for DLA-selected galaxies already in the literature. Thus providing a background on which to base later conclusions.

4 METALLICITIES AND STAR-FORMATION RATES OF OUR GALAXIES

We are principally interested in the emission-line metallicities and SFRs of our observed galaxies. The wavelength coverage of the FORS2 (and SDSS) spectra allows comparison between three empirical strong-line metallicity indicators: N2 (log [N ii]/H\(\alpha\)), O3N2 (log [O iii]/H\(\beta\) – log [N ii]/H\(\alpha\)) and R23 (log ([O iii] + [O ii]) – log H\(\beta\)). R23 requires a dust extinction correction and these were calculated using the Balmer decrement (see Section 2.6). Dust extinction corrections are also essential for realistic SFR measurements (see Section 4.1) and Section 5. As mentioned in Section 2.7, the order of magnitude of these effects is \( \approx 0.1 \) dex on metallicities and up to ten per cent on SFRs. For this work we consider SFRs based on H\(\alpha\) and [O ii] because, whilst direct measurements from H\(\alpha\) are more reliable, the [O ii] indicator is useful when comparing these results with others in the literature (see Section 4.1).

Prior to presenting our new results, we review the results for DLA-selected galaxies already in the literature. Thus providing a background on which to base later conclusions.

4.1 Metallicity and star-formation rates of DLA-selected galaxies

In the literature to date there have been just eight measurements of emission lines in DLA-selected galaxies at \( z < 0.8 \) from which classical strong line metallicity and SFR indicators can be derived (Lacy et al. 2003; Chen et al. 2005; Gharanfoli et al. 2007). This is in no small part due to the difficulty in identifying such DLAs without a UV space spectrograph. Only two of these eight galaxies have H\(\alpha\) line flux measurements; SFRs have been largely based on [O ii] and it has not been possible to estimate dust extinction in these galaxies. As we show in Section 4.3, correcting for dust extinction is vital for obtaining reliable SFR measurements. Here, beginning with the measured integrated line fluxes, we re-derive these SFRs and metallicities using exactly the same assumptions that have been used to derive our Ca ii-selected galaxy SFRs so that a fair comparison can be made between them. The results are shown in Table 6.

R23 is sensitive to reddening so the only reliable metallicities are those for PKS 0439–433 and Q 0809+583 where H\(\alpha\) is detected and an extinction correction can be made. For these objects N2 and O3N2 show that we should consider the upper branch of R23.

4.2 Metallicities of our Ca ii-selected galaxies

There are currently no metallicity measurements of Ca ii absorbers in either emission or absorption. Here we use the metallicity indicators N2(linear) and O3N2, as calibrated by Pettini & Pagel (2004), henceforth PP04, and R23, as calibrated by Kobulnicky, Kennicutt & Pizagno (1999), to provide the first emission-line metallicity measurements. Where there was no line detection for [N ii], [O iii] or [O ii] lines, 3\sigma upper limits were used. J0912+5939 does not have an H\(\beta\) detection, as previously described (see Section 2.6). Therefore, we do not give results for metallicities involving H\(\beta\) in this case. The results are collected in Table 7.

All the measured metallicities are around or above the solar value of 8.66 ± 0.05 (Asplund et al. 2005). In this regime the strong line metallicity indicators are poorly calibrated despite extensive studies (e.g. Bresolin 2006). Due to the small number of known supersolar metallicity galaxies which are bright enough to study. For this

\[1\] Chen et al. (2003).

\[2\] Gharanfoli et al. (2007).

\[3\] Lacy et al. (2003).

\[4\] Whilst more modern calibrations exist, they also include more parameters, hence we utilize this R23 calibration. It will make, at most, a 0.1 dex difference to the R23 results.

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**Table 6.** SFRs and metallicities for DLA-selected galaxies at \( z < 0.8 \) from the literature. Systematic errors are likely of the order 0.3 dex for metallicities and up to ten per cent for SFRs, respectively. See individual references for detailed discussion of the major sources of systematic error in their work.

| Object          | \( z \)     | \( E(B-V)_{\text{gal}} \) | SFR/M\(_{\odot}\) yr\(^{-1}\) | [O ii] \( \lambda_{5007} \) & H\(\alpha\) | N2       | O3N2      | R23 (lower) | R23 (upper) | References |
|-----------------|------------|-----------------------------|-------------------------------|-----------------|-----------------|-----------|-----------|-------------|-------------|------------|
| PKS 0439–433    | 0.101      | 0.211 ± 0.007               | 0.071 ± 0.004                 | 0.55 ± 0.01     | 8.767 ± 0.006   | 8.766 ± 0.006 | 7.34 ± 0.02 | 9.011 ± 0.006 | 1          |
| Q 0738+313      | 0.222      | –                            | <0.003                        | –               | –                | –         | –         | –           | –           | 1          |
| Q 0809+583      | 0.437      | 0.46 ± 0.04                  | 0.49 ± 0.03                   | 0.25 ± 0.02     | 5.1 ± 0.5       | 8.57 ± 0.05   | 8.73 ± 0.04 | 7.23 ± 0.06   | 9.085 ± 0.009 | 1          |
| AO 0235+164     | 0.525      | 1.89 ± 0.05                  | –                             | –               | –                | –         | –         | 8.06 ± 0.05   | 8.55 ± 0.03   | 1          |
| B2 0287+293     | 0.526      | 0.62 ± 0.05                  | –                             | –               | –                | –         | –         | 8.3 ± 0.1     | 8.4 ± 0.1     | 1          |
| LBQS 0058+0155  | 0.612      | 0.27 ± 0.02                  | –                             | –               | –                | –         | –         | –           | –           | 1          |
| FBQS 0051+0041  | 0.740      | 0.9                           | –                             | –               | –                | –         | –         | –           | –           | 3          |

**Table 7.** Ca ii absorption-selected galaxy emission-line metallicities for various strong line indicators. The limit for J0912+5939 is derived without correcting for \( E(B-V) \) or stellar absorption at H\(\alpha\). The systematic errors in each metallicity measurement are \( \sim 0.3 \) dex.

| Object          | N2(linear) | O3N2 | R23(lower) | R23(upper) | References |
|-----------------|------------|------|------------|------------|------------|
| J0019–1053      | 8.67 ± 0.01 | 8.80 ± 0.02 | 7.7 ± 0.1   | 8.94 ± 0.04 | 1          |
| J0912+5939      | < 8.6       | –    | –          | –          | –          |
| J1118–0021      | 8.67 ± 0.003 | 8.79 ± 0.03 | 7.8 ± 0.1   | 8.88 ± 0.04 | 2          |
| J1219–0043      | 8.69 ± 0.05 | 8.84 ± 0.06 | 7.45 ± 0.07 | 9.01 ± 0.02 | 1          |
| J2246+1310      | 8.67 ± 0.01 | 8.71 ± 0.02 | 7.79 ± 0.05 | 8.85 ± 0.02 | 1          |

1Metallicity measurements for this object are strictly lower limits because no correction for \( E(B-V) \) was made.
reason we utilize only the linear form of the N2 index, as laid out by
PPP04, as the cubic form has an upturn precisely in this uncalibrated
metallicity regime. The N2 index is known to saturate around solar
metallicity – there are indications of this in our data when compar-
ing it to the O3N2 and R23 indices. The N2 and O3N2 values
indicate that we should consider the upper branch R23 data.
R23 upper branch metallicities above solar are only calibrated using
photionization models because metal-line cooling makes re-
combination lines too weak to detect in this regime for empirical
calibration. All our metallicities agree within 0.3 dex; flux calibration
errors are therefore not likely to dominate the results and, in
any case, the indicators were designed to be robust against such
effects (Section 4.3). It is, in fact, the 0.3 dex variation between dif-
ferent indicators, due to their calibration which will dominate our
metallicity errors. We can, nevertheless, conclude that these galax-
ies have near-solar metallicities.

It is not currently possible to compare the emission line metal-
lities with absorption line metallicities from strong Ca II systems
because there are none in the literature and new absorption meas-
urements would make a space-borne UV spectrophotograph.
However, if the Ca II absorber population overlap with the DLA pop-
ulation, it is interesting that these emission-line metallicities are
so high compared to the generally low absorption-line metallici-
ties measured in DLAs, i.e. typically ∼0.5 dex at zabs ∼ 0.4. The
galaxies presented here lie on the galaxy metallicity-luminosity rela-
tionship for local galaxies from the KISS survey (Salzer et al.
2005), though they are at the upper end of the luminosity range,
as shown in Fig. 6. Previous studies of absorption-selected galaxy
emission-lines have found similarly high metallicities (e.g. Table 6
Ellison, Kewley & Mallén-Ornelas 2005), so our new results are
perhaps not surprising and confirm that absorption-selected galax-
ies of all flavours can be metal-rich.

4.3 Star-formation rates of our Ca II-selected galaxies

We consider SFRs based on Hα, calibrated by Kennicutt (1998),
and [O II] calibrated by Kewley, Geller & Jansen (2004). These are
both based on a Salpeter (1955) 0.1–100 M⊙ initial mass function, giving

SFR (Hα) = 7.9 × 10^{-42} × L(Hα, erg s^{-1}) M⊙ yr^{-1},

SFR ([O II]) = 6.58 × 10^{-42} × L([O II], erg s^{-1}) M⊙ yr^{-1}.

The measured line fluxes are corrected for extinction and converted
to line luminosities based on their redshifts. No account is taken of
the dispersion in the above luminosity–SFR relationships when
calculating the formal errors. The measured luminosities and SFRs
are in Table 8 We also include an [O II] SFR measurement which has
not been corrected for extinction for comparison with other re-
results in the literature in Section 4.4. Aperture corrections are cal-
culated as described in Section 3.1, and the resulting corrections and
SFRs are shown in Table 9. The systematic difference observed be-
 tween SFRs based on [O II] and Hα is due to their calibration. Based
on its SDSS spectrum Brinchmann et al. (2004) derive a SFR of
7 ± 2 M⊙ yr^{-1} for J1118−0021, which is consistent with our deriva-
tion of 6.2 ± 0.7 M⊙ yr^{-1} from a FORS2 spectrum.

The results based on Hα seem to suggest we are selecting ac-
tively star-forming galaxies. The median SFR for local galaxies,
taken from the NFGS, is 0.5 M⊙ yr^{-1} (Kewley et al. 2002), while
the median SFR in our galaxies is 10.8 M⊙ yr^{-1} (or 6.2 M⊙ yr^{-1}
when lower limits are included). Fig. 8 shows the Hα SFRs mea-
sured in our Ca II-selected galaxies, DLA-selected galaxies and the

Figure 7. A plot of metallicity, based on the N2 index, vs. luminosity (absolute B band magnitude). In cyan are the results for local galaxies from the
KISS survey (Salzer et al. 2005). In red are the Ca II-selected galaxies from this paper. An L∗ galaxy at z = 0 has MB = −20.43 mag (Norberg et al.
2002), a 0.05L∗ galaxy has MB = −17.17 mag. L∗ at the redshift of our
galaxy sample is ∼0.3 mag brighter in the model we adopt. The dashed line
indicates solar metallicity (Asplund et al. 2005). The Ca II-selected galaxies
generally lie near the extreme of the distribution for local galaxies.

Table 8. Ca II absorption-selected galaxy SFRs and line luminosities. Sys-
 tematic errors are up to ten per cent.

| Object       | L / ×10^{40} erg s^{-1} | SFR / M⊙ yr^{-1} |
|--------------|--------------------------|------------------|
|              | [O II]                   | Hα               | [O II]_uncorr | [O II]       |
| J0019−1053   | 210 ± 20                 | 330 ± 40         | 1.37 ± 0.06   | 14 ± 2       | 26 ± 3    |
| J0912+5939   | 3.5 ± 0.7^{†}            | 4.5 ± 0.7        | 0.23 ± 0.04   | –            | 0.35 ± 0.06^{†} |
| J1118−0021   | 29 ± 3                   | 35 ± 3           | 0.14 ± 0.01   | 1.9 ± 0.2    | 2.8 ± 0.3 |
| J1219−0043   | 8.2 ± 0.6^{†}            | 24 ± 2^{†}       | 0.54 ± 0.04   | –            | 1.9 ± 0.1^{†} |
| J2246+1310   | 77 ± 4                   | 91 ± 4           | 0.90 ± 0.03   | 5.1 ± 0.3    | 7.2 ± 0.3 |

1 This luminosity is not corrected for dust extinction due to the absorbing
galaxy.

2 Lower limit to SFR(Hα) based on uncorrected line flux.

Table 9. Geometric slit corrections and corrected Ca II absorption-selected
galaxy SFRs. Systematic errors are up to ten per cent. A correction was
not possible for J0912+5939, for which only a SDSS galaxy spectrum is
available, but it is unlikely to be significant (see Section 3.1). These results
constitute our best estimates of the SFRs in these galaxies.

| Object       | geometric correction | SFR / M⊙ yr^{-1} |
|--------------|-----------------------|------------------|
|              | [O II]                | Hα               |
| J0019−1053   | 1.11                  | 16 ± 2           | 29 ± 3        |
| J1118−0021   | 2.20                  | 4.2 ± 0.4        | 6.2 ± 0.7     |
| J1219−0043   | 1.41                  | 2.7 ± 0.1^{†}    |
| J2246+1310   | 1.50                  | 7.7 ± 0.5        | 10.8 ± 0.5    |

1 Lower limit to SFR(Hα) based on uncorrected line flux.
5 DISCUSSION

The most important results from this work are the galaxy emission line metallicities and SFRs. Before discussing these we briefly review what we have learnt about the general properties of our sample to set the context in which to consider the main results.

5.1 General properties of our Ca ii-selected galaxies

The dominant property of the galaxies in our sample, with reference to the derived metallicities and SFRs, are their \( L^* \) luminosities. It is likely this is a selection bias, which is highlighted by the fact that the lowest luminosity galaxy is one we did not identify through SDSS imaging, but rather through its galaxy spectrum superimposed on the QSO spectrum.

Given their luminosities, one might expect these galaxies to have rotational speeds similar to the MW. The measured H\( \alpha \) line widths of \( \sigma \approx 100 \text{ km s}^{-1} \) provide lower limits which are not inconsistent with this. However, given a random distribution of galaxy inclinations one might also expect some of these lower limits to be nearer the MW rotational speed if the H\( \alpha \) emission is truly tracing galactic rotation. Focusing on their velocity structures using with long-slit or integral field spectra would demonstrate whether this is the case or whether the H\( \alpha \) emission traces other processes like outflows from the H\( \alpha \) regions.

The QSO–galaxy impact parameters in Table 5 are similar to those of DLAs (e.g. Kewley et al. 2002) which is consistent with the Ca ii absorber population significantly overlapping with that of DLAs (WHP06). Whilst this somewhat justifies our comparison between DLA and Ca ii absorber SFRs, it is based on small number statistics. One might generally expect there to be a greater distribution of Ca ii absorber impact parameters; DLAs and other absorbers, such as those with strong Mg \( \alpha \), certainly have a broader impact parameter distribution. Recent \( K^\prime \)-band imaging of Ca ii absorbers by Hewett & Wild (2007) confirms this at high redshift, where they find mean impact parameters of 24 kpc. However, it is not obvious how our selection procedure would bias the data in this respect.

The SED fits to the sample suggest that the Ca ii-selected galaxies are normal star-forming spirals. Since spirals should have relatively high gas cross-sections, it is not surprising that such galaxies are selected via their absorption properties. However, in general, direct imaging of low-redshift DLAs reveals a mix of host galaxy types, including irregular, spiral and low-surface brightness galaxies (e.g. Le Brun et al. 1997, Rao et al. 2003). This is supported by a blind 21-cm emission study of local galaxies (Ryan-Weber, Webster & Staveley-Smith 2003). It is unclear whether the predominance of spirals in our Ca ii-selected sample is a consequence of the Ca ii selection itself or our aforementioned luminosity bias. More detailed imaging and spectroscopic study of velocity structure of a larger sample is required to make more specific conclusions about the general properties of these Ca ii-selected galaxies and to avoid the luminosity bias inherent in our current sample. Nevertheless, some interesting conclusions can be drawn from the metallicities and SFRs measured in our galaxies.

5.2 Metals in Ca ii-selected galaxies

At least four out of the five galaxies studied are metal-rich, with solar or super-solar oxygen abundances (Table 4). Interestingly, similar values have been found in both cases where emission line abundances could be deduced in the host galaxies of known DLAs at \( z < 0.8 \) (Table 5). Potentially, the oxygen abundance...
could be significantly super-solar in the galaxies where we estimate \((O/H)_z = (O/H)_0\), because the strong-line indices at our disposal are poorly calibrated in the super-solar regime and the whole issue of how best to measure metallicities in nebulae with \((O/H) > (O/H)_0\) remains controversial (e.g. Bresolin 2006; Peimbert et al. 2006).

Such high metallicities contrast with the generally sub-solar element abundances measured in most DLAs from interstellar absorption lines. In the latest census by Kulkarni et al. (2006), the average (column density weighted) metallicity of confirmed DLAs is \(\langle Z_{\text{DLA}} \rangle \approx 1/7 Z_\odot \) at \(\langle z \rangle \approx 0.5\). There are several reasons which could explain such a dichotomy.

One possibility is that such differences arise from the fact that different elements are being considered in the two sets of measurements. While emission line abundances measure \((O/H)\), the interstellar determinations of \(Z_{\text{DLA}}\) are based on Zn which behaves like a Fe-peak element (e.g. Chen, Nissen & Zhao 2004). However, in most DLAs – and indeed in Galactic stars – the \(\alpha\)-element enhancement expected at metallicities \((Fe/H) = -0.82\) (i.e. \(1/7\) solar) is less than a factor of three. Thus, this possibility is unlikely to explain fully the difference between our observations here and the typical DLA absorption line abundances.

A second option, which has already been mentioned, is the luminosity bias of our selection. As we favoured brighter galaxies in this initial study, we are also likely to have selected the more metal-rich galaxies within the presumably broad distribution of metallicities of DLA hosts (given the wide spread of values of \([Zn/H]\) measured in absorption).

Thirdly, it is conceivable that in some cases we may have misidentified the absorbing galaxy and that the host galaxy of the DLA is a low luminosity dwarf below the detection limit of our images located close to the bright galaxy we have identified. Galaxy clustering certainly makes this a possibility in some instances, although it is unlikely that we should be misled in every case. The prevalence of this scenario is being tested by searches for galaxies near faded gamma-ray bursts (e.g. Jakobsson et al. 2004; Ellison et al. 2006) and for DLA galaxy hosts along sight-lines where high-\(z\) Lyman-limit systems block the QSO flux from blue imaging bands (O’Meara, Chen & Kaplan 2006).

A fourth possibility, and potentially the most interesting to explore further, is that there may be systematic differences between emission- and absorption-based abundances if the two sets of data sample different regions within the galaxies. One could envisage a scenario where the nebular emission lines are stronger in the inner, higher surface brightness, regions, while the cross-section of the neutral gas producing the DLA is larger in the outer parts. In the presence of radial abundance gradients, a systematic offset of the sign and magnitude observed could result. This possibility has already been discussed by Chen et al. (2005) and Bowen et al. (2005) and, while certainly plausible, its importance has yet to be quantified. What is required is a direct comparison of emission- and absorption-based abundances in the same galaxies and using elements which share the same stellar nucleosynthesis and degree of interstellar depletion. These requirements have so far been met in only one case, studied by Bowen et al. (2005), where no offset was found between nebular and DLA abundances. However, the galaxy in question is a dwarf spiral where no abundance gradient was expected over the radial distance probed.

In this respect, the sample of galaxies presented here, while still small, constitutes a prime set of targets for future ultraviolet observations once the Cosmic Origins spectrograph (COS) is installed on a refurbished HST. In particular, by measuring the abundance of sulphur (an undepleted, \(\alpha\)-capture element) in the Ca \(\alpha\) absorption systems, it will be possible to (i) determine a quantitative estimate of radial abundance gradients in galaxies at earlier epochs – a parameter which is a fundamental importance in galactic chemical evolution models (e.g. Carigi et al. 2005) and (ii) clarify the reasons why \(Z_{\text{DLA}}\) remains sub-solar at all redshifts.

Recently, Herbert-Fort et al. (2006) studied ‘metal strong’ DLAs (MSDLAs), which are defined to have \(\log (N_{\text{Znii}}) \geq 13.15\) or \(\log (N_{\text{SiII}}) \geq 15.95\), where the column densities are measured in atoms \(cm^{-2}\). Given the high metallicities of our Ca \(\alpha\)-selected galaxies, it could be that the Ca \(\alpha\) absorber population overlaps more strongly with that of MSDLAs compared to that of DLAs in general. Studying the Zn \(\alpha\) and Si \(\alpha\) line strengths in a sample of Ca \(\alpha\) absorbers would be interesting in this respect. This is already possible at absorption redshifts \(0.65 \lesssim z_{\text{abs}} \lesssim 1.3\) since the Ca \(\alpha\) and Zn \(\alpha\) transitions fall in the optical region. We have begun such a study with high resolution QSO spectra from the VLT. Clearly, for the redshifts studied here \(z_{\text{abs}} \lesssim 0.5\), UV spectra are required.

5.3 Star formation in Ca \(\alpha\)-selected galaxies

The galaxies in our sample are actively star-forming. Luminosity bias probably affects the measured SFRs more than the measured metallicities because the observed luminosity is, in part, caused by current star formation, while the high metallicities more strongly reflect past star formation. Thus, although it is possible that most low-\(z\) Ca \(\alpha\)-selected galaxies could have near solar metallicities, it is unlikely they all have such high SFRs. We reiterate that the systematic effects discussed in Section 2.7 will have reduced the SFRs we measure and so all our SFRs are technically lower limits.

It is clear from Fig. 9 that the DLA-selected galaxies in the literature have similar \([O\alpha]\) emission-line SFRs, before correcting for extinction, to our Ca \(\alpha\)-selected galaxies. This is unsurprising, given that they were generally selected in a similar way to how we chose the Ca \(\alpha\) galaxy sample (i.e. relatively bright galaxies were found close to the QSO sight-lines). However, what is surprising is that this suggests that the DLA-selected galaxies should have similar extinction corrected SFRs to our Ca \(\alpha\) galaxies (assuming the star formation regions in those galaxies have similar levels of dust extinction); i.e. the DLA galaxies are also actively star-forming. The amount of star-formation associated with these DLAs has therefore been underestimated in the literature. Extinction corrections are important in star-forming regions, irrespective of the amount of dust associated with the absorber itself, which is generally very low (e.g. Ellison, Hall & Lira 2003; Murphy & Liske 2004; WHPO7). Previous authors have generally found much lower rates of star-formation associated with DLAs (e.g. Wolfe & Chen 2006; Hopkins et al. 2005; Zwaan et al. 2005; Wolfe et al. 2003). This is perhaps an indication that DLAs, whilst not being the sites of \textit{in situ} star-formation, are nonetheless closely associated with it.

If one naively attempts to directly compare our sample’s \([O\alpha]\) SFRs to the higher redshift measurement of WHPO7, who stack many Ca \(\alpha\) absorption spectra to measure an SFR based on \([O\alpha]\), one concludes that our SFRs are too high to be applicable to the general Ca \(\alpha\)-selected galaxy population. This is most likely due to differences between the impact parameter and luminosity distributions of the two samples. For example, two broad scenarios could plausibly explain the difference between the relatively unbiased WHPO7 results and our own:

(i) the relatively low \([O\alpha]\) star-formation signal measured in WHPO7 could be dominated by \( \lesssim 1\) galaxies at low impact parameters (i.e. inside the SDSS fibre radius). These galaxies domi-
nate the evolution in the Madau diagram. That is, only some Ca\textsc{ii} absorbers in this scenario would be closely associated with the sites of star-formation. Assuming this to be true, the following simple correction to the WHP07 results allows a comparison with our more directly measured SFRs, thereby providing a crude estimate of the luminosity bias in our sample. Firstly, at high redshift Hewett & Wild (2007) find that only thirty per cent of the excess galaxy luminosity associated with the Ca\textsc{ii} absorbers falls within the SDSS fibres, thus the WHP07 results must be altered to account for this. Secondly, WHP07 corrected their SFR measurement only for the very small dust extinction found in the absorbers themselves, not that appropriate to \( \sim L^\ast \) galaxies. For local galaxies, the average \( E(B-V) \) is 0.36 mag (Kennicutt 1992), corresponding to an extinction factor of 4.54 at [O\textsc{ii}]. Thus, the WHP07 SFR of 0.2 \( M_\odot \) yr\(^{-1} \) translates to 100/30 \( \times 4.54 \times 0.2 \) = 3.0 \( M_\odot \) yr\(^{-1} \) in this scenario. This is 0.32 times the mean dust-corrected SFR in our sample (9.3 \( M_\odot \) yr\(^{-1} \)). From the Madau diagram (Hopkins 2004), we expect a factor of \( \sim 3.5 \) drop in SFR density between the mean redshifts of the WHP07 sample (\( \bar{z} = 0.850 \)) and ours (\( \bar{z} = 0.285 \)). That is, our galaxy sample would appear to be \( \sim 3.5/0.32 = 11 \) times more star-forming than expected for Ca\textsc{ii}-selected galaxies at low-\( z \).

(ii) Star-formation could be ubiquitous amongst Ca\textsc{ii} absorbers. In this case its signature would be dominated by low level \textit{in situ} star-formation and the required reddening corrections would be low, i.e. those used by WHP07. If this scenario were true then we have no basis on which to compare our low redshift results to this higher redshift one. However, our luminosity bias would be significant since our galaxy sample would represent highly unusual Ca\textsc{ii} galaxies.

Knowing \( E(B-V) \) from the galaxy emission lines in the WHP07 sample would help distinguish between these scenarios. Unfortunately, their stacked Ca\textsc{ii} absorber spectrum has too low S/N to put meaningful constraints on \( E(B-V) \) via H\beta and it is not clear that the H\beta limit from their stacked Mg\textsc{ii} DLA sample applies equally to the Ca\textsc{ii} sample. Nevertheless, the limits on \( E(B-V) \) from their Mg\textsc{ii} sample favour scenario (ii) above. Thus, while WHP07 favour low levels of \textit{in situ} star-formation associated with Ca\textsc{ii} absorbers and DLAs, our work provides clear examples of highly star-forming Ca\textsc{ii} galaxies. It seems likely that some mix of these scenarios more closely reflects reality. Indeed, Hewett & Wild (2007) find that their higher redshift Ca\textsc{ii} absorbers have a stronger galaxy luminosity–dependence on the absorber cross-section (\( \sigma \propto L^{0.75} \)) compared with that for other QALs, such as Mg\textsc{ii} absorbers (\( \sigma \propto L^{0.4} \)). A study of the SFRs in less luminous Ca\textsc{ii}-selected galaxies will help to elucidate the situation; we are currently undertaking such a study on the Gemini telescope.

6 CONCLUSIONS

We have presented the first direct study of Ca\textsc{ii}-selected galaxies. The five galaxies in our sample are metal rich and actively star-forming. We have also demonstrated the importance of both stellar absorption along the Balmer series and dust extinction in such galaxy studies. Prior to this work, the literature contained emission-line fluxes of just seven DLA-selected galaxies at \( z < 0.8 \) from which SFRs could be derived. In only two of these galaxies was it possible to make the all-important dust corrections required for a robust interpretation of the observed SFRs. Given the probable overlap between the Ca\textsc{ii} and DLA populations, the current work represents a significant contribution to our fledging understanding of low-\( z \) DLA-selected galaxies and the galaxy–absorber connection.

It is likely that luminosity bias, introduced during our sample selection, is an important factor in the high metallicities and SFRs we observe. As such, it is unlikely that the SFRs presented here are applicable to all Ca\textsc{ii}-selected galaxies. This is probably also true of the super-solar metallicities measured, though the slope and scatter in the luminosity–metallicity relationship ensures that the effect should be less pronounced. Further observations of a larger, less biased sample of Ca\textsc{ii}-selected galaxies is required to confirm this. A larger sample would also allow identification of general trends in Ca\textsc{ii}-selected galaxy properties, such as the relationships between luminosity, SFR, metallicity, impact parameter, morphology etc.

It may be possible to estimate this luminosity bias by comparison with the results of WHP07 who derived an [O\textsc{ii}]-based SFR from stacked SDSS spectra of higher-redshift Ca\textsc{ii} absorbers. However, such a comparison is only possible if one assumes that the star-formation signal originates from some fraction of Ca\textsc{ii}-selected galaxies with low impact parameters and \( \sim L^\ast \) luminosities. Another plausible scenario (and one favoured by WHP07) is that most strong Ca\textsc{ii} absorbers host low levels of \textit{in situ} star formation. In this case, the luminosity bias in our sample cannot be determined but it clearly must be large since we do observe some highly star forming galaxies. Future observations of a more representative Ca\textsc{ii}-selected galaxy sample will focus on quantifying the relative importance of these scenarios.

Rereddening corrections and proper treatment of the stellar absorption at H\beta and H\alpha proved vital for a robust measurement of the SFRs in our Ca\textsc{ii}-selected galaxies. If no dust extinction corrections were applied, our SFRs would be a factor of 20 smaller and would be consistent with the low SFRs reported in previous low-\( z \) emission-line studies of DLA host galaxies that did not apply a dust correction. It is therefore likely that previous conclusions about the apparently low SFRs in DLA-selected galaxies should be revised. Indeed, it is probable that the majority of such galaxies studied, via their emission-lines, to date are actively star-forming.

The observed slow increase in DLA metallicity from high redshifts to the current epoch has raised concerns that DLAs may not be reliable tracers of star formation in the Universe. However, the fact that we find high emission-line metallicities and SFRs in Ca\textsc{ii}-selected galaxies at low-\( z \) is consistent with previous studies which conclude that DLAs can be closely linked to star formation without themselves having high absorption-line metallicities. A study comparing absorption- and emission-line metallicities as a function of impact parameter would be an excellent way to assess this more directly; it would constrain the relative contributions of dust and metallicity gradients to any observed discrepancies. A handful of individual DLA galaxies have already been studied in emission and absorption (Bowen et al. 2005, Schulte-Ladbeck et al. 2004, Chen et al. 2005), but a more complete sample of such galaxies is required for a comprehensive study. Since Ca\textsc{ii} absorbers and their host galaxies are relatively easy to identify at \( z < 0.5 \), they will be the ideal targets for such a study when the community next has access to a space-borne UV spectrograph. Those observations would also be vital for quantifying the (likely strong) overlap between the Ca\textsc{ii} and DLA absorber populations.

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