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Dust depletion, chemical uniformity and environment of Ca II H&K quasar absorbers

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ABSTRACT
Ca II λ3934, 3969 absorbers, which are likely to be a subset of damped Lyman α systems, are the most dusty quasar absorbers known, with an order of magnitude more extinction in E(B−V) than other absorption systems. There is also evidence that Ca II absorbers trace galaxies with more ongoing star-formation than the average quasar absorber. Despite this, relatively little is known in detail about these unusual absorption systems. Here we present the first high resolution spectroscopic study of 19 Ca II quasar absorbers, in the range 0.6 ≤ zabs ≤ 1.2, with Ca II λ3934 equivalent widths, W03934 > 0.2 Å. Their general elemental depletion patterns are found to be similar to measurements in the warm halo phase of the Milky Way (MW) and Magellanic Clouds interstellar medium. Dust depletions and α-enrichments profiles of subsamples of 7 and 3 absorbers, respectively, are measured using a combination of Voigt profile fitting and apparent optical depth techniques. Deviations in [Cr/Zn] ~ 0.3 ± 0.1 dex and in [Si/Fe] ≥ 0.8 ± 0.1 dex are detected across the profile of one absorber, which we attribute to differential dust depletion. The remaining absorbers have < 0.3 dex (3σ limit) variation in [Cr/Zn], much like the general DLA population, though the dustiest Ca II absorbers, those with W03934 > 0.7 Å, remain relatively unprobed in our sample. A limit on electron densities in Ca II absorbers, n_e < 0.1 cm⁻³, is derived using the ratio of neutral and singly ionised species and assuming a MW-like radiation field. These electron densities may imply hydrogen densities sufficient for the presence of molecular hydrogen in the absorbers. The Ca II absorber sample comprises a wide range of velocity widths, Δv90 = 50 – 470 km s⁻¹, and velocity structures, thus a range of physical models for their origin, from simple discs to galactic outflows and mergers, would be required to explain the observations.

Key words: galaxies: ISM – quasars: absorption lines

1 INTRODUCTION
Quasar absorption line systems are understood to be probes of galaxies not subject to the luminosity bias of traditional surveys, being instead biased by their gas content and galaxy cross-section. Despite this, our exact understanding of how absorbers and galaxies are related is uncertain due to the difficulty of interpreting absorption line characteristics in the context of the associated galaxy. Damped Lyman α systems (DLAs), defined by virtue of having neutral hydrogen column densities N_H ≥ 2 × 10¹⁹ atoms cm⁻², are some of the best studied absorption systems. In particular, it was postulated that DLAs may be the reservoirs of neutral gas in the Universe from which stars form because the amount of neutral gas in DLAs at z ~ 3 is similar to the amount of gas locked up in stars today (Wolf3934; Wolfe, Gawiser & Prochaska 2005). Attempts to measure the star-formation associated with DLAs through a variety of direct and indirect techniques (e.g. Wolfe, Prochaska & Gawiser 2003; Chen, Kennicutt Jr. & Rauch 2005; Wolfe & Chen 2006) have met with limited success, generally finding low star-formation rates.

Recently, Wild & Hewett (2005) used the statistical power of the Sloan Digital Sky Survey (SDSS) to study the rare, so-called strong Ca II absorbers (those with rest-frame equivalent widths, W03934 > 0.2 Å). Wild & Hewett (2005) postulated that Ca II absorbers were an unusual sub-class of DLAs because lines of sight through our own Galaxy with similar strengths of Ca II absorbers have neutral hydrogen column densities consistent with DLAs. Furthermore, Wild & Hewett (2005) found that the Mg II equivalent widths of Ca II absorbers are large (W02796 > 1.0 Å), thus they have a high probability of being DLAs (Rao & Turnshek 2000). The observed sample of Ca II absorbers has also been found to be much more dusty than either the general DLA population or strong Mg II absorbers, with average E(B−V) ~ 0.1 mag (Wild, Hewett & Pettini 2006, henceforth WHP06), compared to...
$E(B-V) \simeq 0.013$ mag for Mg II absorbers (WHP06, York et al. 2006) and $E(B-V) < 0.02$ mag for DLAs (Murphy & Liske 2004; Vladilo et al. 2008). The low levels of dust in DLAs are confirmed by studies of radio-selected quasars, which find little evidence for optical quasar drop-outs due to dusty DLAs (Ellison et al. 2001, Ellison, Hall & Lid 2005). Nonetheless, the presence of dust detected by WHP06 means that Ca II absorbers are significantly under-represented in existing samples of DLAs, a conclusion consistent with those of Nestor et al. (2008), who find that only $\sim 10$ per cent of DLAs possess very strong, $W_{\lambda 2796} > 0.5$ Å, Ca II absorption. The suggested number of optical quasar drop-outs due to dusty Ca II absorbers is still consistent with the statistics of the Ellison et al. (2001) radio-selected quasar sample. Nestor et al. (2008) also find indirect indications from photo-ionisation modeling, constrained by their observations, that Ca II absorbers host molecular hydrogen.

In addition to these indirect indicators of star-formation activity, such as dust and molecular hydrogen, direct studies at both intermediate and low redshift have shown Ca II absorbers to be associated more strongly with star formation than other absorbers. At $z \sim 1$ Ca II absorbers are found to have mean in situ star formation rates (SFRs) from $0.11 - 0.48$ M$_\odot$ yr$^{-1}$ compared to just $0.11 - 0.14$ M$_\odot$ yr$^{-1}$ for DLAs (Wild, Hewett & Pettini 2007). These SFRs are as measured inside the 3$''$ diameter SDSS fibre centred on each quasar and thus do not account for star-formation in the absorber host galaxy if it falls outside this radius. At lower redshifts, $z \lesssim 0.4$, direct measurements from the host galaxies of Ca II absorbers give SFRs in the range $0.3 - 30$ M$_\odot$ yr$^{-1}$, though it is likely the work is biased towards $L^*$ galaxies (Zych et al. 2007).

Thus, there is now much evidence to suggest Ca II absorbers are associated with star-formation, at least to some extent, both with direct measurements of the star formation rate and through signatures generally associated with star formation such as dust and molecular hydrogen. However, few details of why Ca II absorbers might trace star-formation more readily than other absorbers are understood. Nor do we know much about the physical environment of the absorbers themselves (rather than their host galaxies).

In this paper we present the first results of a high resolution study of the absorbing gas using observations from the Ultra-Violet Echelle Spectrograph (UVES) at the VLT and the HIgh Resolution Echelle Spectrograph (HIRES) at Keck. With these data we are able to study the dust depletion and chemical uniformity (n enhancement) of individual absorbers as well as constrain the physical environment giving rise to the absorbing gas based on the velocity structure of the absorber.

The paper is structured as follows: in Section 2 we present the sample selection, observations, data reduction and analysis techniques used in the rest of the paper. Section 3 contains the results of our analysis, divided into dust depletion, enrichment and environment sub-sections. Section 4 places these results into context with more general results from the literature and finally, Section 5 summarizes the main points from the paper.

2 SAMPLE SELECTION, OBSERVATIONS, DATA REDUCTION AND ANALYSIS

2.1 Selection

The Ca II $\lambda\lambda$3934, 3969 absorption lines are relatively weak and thus detection of the Mg II $\lambda\lambda$2796, 2803 absorption lines at the same redshift are required to confirm that the absorption system is real. In practice no real Ca II absorbers are detected with $W_{\lambda 2796} < 0.5$ Å, thus this can be used as a constraint to weed out false-positive detections (Wild & Hewett 2005, Wild et al. 2006). Absorbers were identified by searching for features with rest frame equivalent width, $W_{\lambda 3934} \gtrsim 0.2$ Å at 4$\sigma$ significance in the sample of all 58835 SDSS DR4 quasars classified by having ‘specClass’ $\equiv 3$ or 4 in the SDSS. To confirm a detection as real, it was also required that the Ca II $\lambda 3969$ line equivalent width had a significance $> 1$ $\sigma$ and that Mg II $\lambda 2796$ was detected at $> 6$ $\sigma$ significance with $W_{\lambda 2796} \gtrsim 0.5$ Å. This requirement implies a minimum velocity width $\gtrsim 50$ km s$^{-1}$ for our absorbers, which being at the lower limit of the velocity width distribution for DLAs will not strongly bias any comparison between Ca II absorbers and DLAs (See Section 4.4). Absorbers separated by less than $500$ km s$^{-1}$ were classified as a single absorption system. For the purposes of this project the sample was restricted to $z_{\text{abs}} > 0.73$ so that Zn II $\lambda 2026$ was above 3500 Å, below which the efficiency of UVES (and HIRES) begins to drop more rapidly. Finally, suitable candidates for follow-up high resolution observations required the Zn and Cr transitions to lie outside the Ly$\alpha$ forest.

Targets with $g$-band magnitudes $\lesssim 18.5$ mag were selected to achieve signal-to-noise ratio (SNR) $\sim 10$ per pix in the continuum at the wavelength of Zn II $\lambda 2026$, 2062 and Cr II $\lambda 2056$, 2062, 2066. Declination was restricted to allow observations from the VLT at Paranal in Chile (except for the one target observed with Keck in Hawaii) and R.A. was scheduling dependent.

These SDSS-selected absorbers were complemented by a search through the ESO/UVES science archive for any absorbers which also exhibited strong Ca II absorption at the limits defined above.

2.2 Observations

The new UVES data were taken in service mode during the period 2007 May 18 – July 25 as part of ESO observing programme 79.A-0656. The programme was not completed, so we only have partial data on some absorbers, therefore we will highlight in each section which absorbers have data which contributed to the respective analyses. We observed J0334–0711 on 2008 January 12 for one 2700 s exposure with the C1 decker on Keck/HIRESb (Vogt et al. 1994). The observations are summarised in Table 1. The emission redshifts are as given by SDSS and the absorber redshifts are as measured from the SDSS Ca II detections. For all UVES observations the slit width was 1.2", which was comparable to the seeing in all cases. The data were binned, 2 $\times$ 2, to improve the SNR. All observations were taken with the slit at the parallactic angle to compensate for atmospheric dispersion.

To supplement these newly observed data we include 12 Ca II absorbers detected in quasar spectra from the ESO/UVES science archive (See Table 2). Equivalent width measurements of Ca II $\lambda 3934$ and Mg II $\lambda 2796$ for all the absorbers are available in Table 1.

2.3 Data reduction

The UVES data were reduced using the new UVES Common Pipeline Language (CPL) pipeline from ESO. The Keck/HIRESb data were reduced using the HIRedux software package1 bundled

http://www.ucolick.org/~xavier/HIRedux/index.html
\( \lambda \) is the UVES dichroic central wavelength measured in nm.

The individual orders and exposures were then air−vacuum and heliocentric corrected and combined using uves popler\(^4\). During combination all spectra were rebinned to a 2.5 km s\(^{-1}\) pixel scale. Both instruments have FWHM (Full-Width Half-Maximum) \( \sim 7 \) km s\(^{-1}\) spectral resolution, thereby giving \( \sim 3 \) pixel sampling for unresolved features.

### 2.4 Analysis

The analysis of the final spectra involves two main approaches. Firstly, abundance profile analysis based on Voigt profile fits to the various ionic transition\(^2\) in the absorber and secondly a comparison of the velocity structure of these absorbers to data and models in the literature. The first approach allows us to make a quantitative analysis of chemical and dust-depletion uniformity and, in principle, chemical enrichment history via models of relative abundances of \( \alpha \) and Fe-peak elements. Unfortunately, the wavelength coverage and SNR of the spectra are not sufficient for a full decomposition of the star-formation history (e.g. Dessauges-Zavadsky et al.\(^4\) 2007). Nonetheless non-uniformity in the \( \alpha \) enrichment and dust depletion

### Table 1

A summary of the observations taken with UVES during ESO Period 79 and HIRES for this work. We define the resolving power, \( R \equiv \Delta \lambda/\lambda \), where \( \lambda \) is the UVES dichroic central wavelength measured in nm.

| Object               | SDSS name                     | \( g \)-band mag. | \( \zeta_{em} \) | \( \zeta_{abs} \) | Dichroic | \( R \) | Total exposure time [s] |
|----------------------|--------------------------------|-------------------|-----------------|-----------------|----------|--------|------------------------|
| J0334−0711\(^1\)     | SDSSJ033438.28−071149.0        | 17.25             | 0.635           | 0.59760          | −        | 54000  | 2700                   |
| J0846+0529           | SDSSJ084650.44+052946.0        | 17.65             | 1.052           | 0.74294          | 390      | 54256  | 2930                   |
| J0953+0801           | SDSSJ095352.69+080103.6        | 17.89             | 1.720           | 1.02316          | 390      | 54240  | 2930                   |
| J1005+1157           | SDSSJ100523.73+115712.4        | 18.20             | 1.657           | 0.83460          | 390      | 54259  | 2930                   |
| J1129+0204           | SDSSJ112932.71+020422.7        | 17.65             | 1.193           | 0.96497          | 390      | 54260  | 2930                   |
| J1203+1028           | SDSSJ120342.24+102831.7        | 17.88             | 1.888           | 0.74630          | 390      | 54280  | 9805                   |
| J1430+0149           | SDSSJ143040.83+014939.9        | 17.79             | 2.113           | 1.24180          | 437      | 54252  | 12147                  |

Table 2. A summary of spectra taken from the ESO/UVES Science Archive for this work, with an indication of how the data is used. Magnitudes are SDSS \( g \)-band values unless otherwise referenced. B1950 names are included for convenience.

| Object               | \( \alpha \) (J2000) | \( \delta \) (J2000) | B1950 | magnitude | \( \zeta_{em} \) | \( \zeta_{abs} \) | Notes\(^1\) |
|----------------------|---------------------|---------------------|-------|-----------|-----------------|-----------------|-----------|
| J0004−4157           | 00 04 48.07         | -41 57 27.7         | Q0002−4214 | 17.2 V\(^2\) | 2.760           | 0.83663         | V         |
| J0256+0110           | 02 56 07.24         | +01 10 38.6         | Q0253+0058 | 18.95 g     | 1.348           | 0.72578         | V         |
| J0407−4410           | 04 07 18.08         | -44 10 14.6         | Q0405−4418 | 17.6 B\(^3\) | 3.000           | 0.81841         | V         |
| J0517−4410           | 05 17 07.82         | -44 10 55.4         | Q0515−4414 | 14.9 V\(^4\) | 1.710           | 1.14955 V, D, A |         |
| J0830+2410           | 08 30 52.09         | +24 10 59.8         | Q0827+243  | 17.4 g      | 0.940           | 0.52477         | V         |
| J1028−0100           | 10 28 37.02         | -01 00 27.6         | Q1026−0045 | 17.2 g      | 1.531           | 0.63214         | V         |
| J1107+0048           | 11 07 29.04         | +00 48 11.2         | Q1104−0104 | 17.7 g      | 1.392           | 0.74030 V, D   |         |
| J1130−1449           | 11 30 07.05         | -14 49 27.4         | Q1127−145  | 16.9 V\(^2\) | 1.184           | 0.31272         | V         |
| J1211+0130           | 12 11 40.60         | +10 30 02.0         | Q1209+1046 | 18.1 g      | 2.192           | 0.62962         | V         |
| J1232−0224           | 12 32 00.01         | -02 24 04.3         | Q1229−021  | 17.2 g      | 1.043           | 0.39544         | V         |
| J1323−0021           | 13 23 23.79         | -00 21 55.3         | Q1320−0006 | 18.5 g      | 1.388           | 0.71608         | V         |
| J2328+0022           | 23 28 20.37         | +00 22 38.2         | Q2325+0006 | 18.0 g      | 1.308           | 0.65200         | V         |

Table 2. A summary of spectra taken from the ESO/UVES Science Archive for this work, with an indication of how the data is used. Magnitudes are SDSS \( g \)-band values unless otherwise referenced. B1950 names are included for convenience.

\(^{1}\) HIRESb target which used the C1 decker with FWHM \( \sim 7 \) km s\(^{-1}\) spectral resolution

\(^{2}\) http://www.ucolick.org/~xavier/IDL/index.html

\(^{3}\) Transition wavelengths and oscillator strengths were taken from Morton (2003).

\(^{4}\) UVES POPLER is available from http://www.astronomy.swin.edu.au/~mmurphy/UVES_poper.html

\(^{5}\) Rao, Turnshek & Nestor (2006)

\(^{6}\) Reimers et al. (1998)
of the absorbers will provide clues as to the physical environment of the absorbing gas (See Sections [3.2] & [4.3]). Furthermore, the electron density of the absorbing cloud can be constrained from measured limits from the $N$(Fe)/$N$(Fe) and $N$(Mg)/$N$(Mg) ratios. The second approach involves study of the velocity profiles and widths of each absorber, allowing qualitative assessment of the physical models able to explain the velocity structure of the gas, such as simple galaxy discs, haloes, inflows or outflows.

### 2.4.1 Column densities and equivalent widths

We used vpfit\(^5\) to fit multiple velocity component Voigt profiles to each unsaturated metal ion transition of interest in each absorber. The transitions of interest for our analysis were Fe\(^{ii}\), Mg\(^{ii}\), Si\(^{ii}\), Zn\(^{ii}\), Cr\(^{ii}\), Mn\(^{ii}\), Ti\(^{ii}\) and Al\(^{ii}\). An initial guess for the fit was constructed from Fe\(^{ii}\) as multiple Fe\(^{ii}\) transitions at a variety of wavelengths were usually observed, which allows vpfit to constrain the velocity structure more accurately. For the remaining transitions fitted, the redshifts and Doppler parameters, $b$, of individual components were tied to Fe\(^{ii}\) (or Mg\(^{ii}\)) when Fe\(^{ii}\) was unavailable, whilst column densities for each component were allowed to vary freely. At the resolution and SNR of the spectra we saw no evidence for these transitions requiring independent redshifts and $b$ parameters.

The total column densities were reported directly from vpfit, which allows for a more accurate estimate of the formal error because it alleviates the problem of blending between neighbouring components, which produces degeneracies between column densities and $b$ parameters for those components (see vpfit documentation). Upper limits were taken at 3\(\sigma\) using the error reported from vpfit.

Both the Mg\(^{ii}\)\(\lambda2026\) and Zn\(^{ii}\)\(\lambda2026\) and Zn\(^{ii}\)\(\lambda2062\) and Cr\(^{ii}\)\(\lambda2062\) lines are usually blended due to the velocity width of the absorption system. Despite this blending the fits to these lines are not degenerate; vpfit simultaneously fits these lines, along with unblended lines such as Cr\(^{ii}\)\(\lambda2056\) and Mg\(^{ii}\)\(\lambda2082\), using the pre-determined velocity structure. The spectra are always of sufficient wavelength coverage with high enough SNR for a non-degenerate fit to be reached. For example the Zn\(^{ii}\) velocity structure may appear uncertain if the absorption profile is sufficiently wide to blend together the Zn\(^{ii}\)\(\lambda2026\) and Mg\(^{ii}\)\(\lambda2082\) profile\(^6\) and also the Zn\(^{ii}\)\(\lambda2062\) and Cr\(^{ii}\)\(\lambda2062\) profiles. However, since the Cr\(^{ii}\) velocity structure is independently determined by Cr\(^{ii}\)\(\lambda2056\) and/or Cr\(^{ii}\)\(\lambda2066\), and since fitting the Mg\(^{ii}\)\(\lambda2082\) profile determines the Mg\(^{ii}\)\(\lambda2026\) profile, the Zn\(^{ii}\) velocity structure can be recovered reliably.

When all transitions of a given ionic species are saturated (e.g. Mg\(^{ii}\)) the column density of the species is unconstrained by Voigt profile fitting. Instead, for Mg\(^{ii}\)\(\lambda2796,\lambda2803\) we measure the equivalent width of the profile, which gives an indication of the velocity spread in the absorber. The equivalent widths were calculated by summing across each pixel, $i$, in the profile

$$W = \sum_i (1 - f_i) \Delta l_i$$  \hspace{1cm} (1)$$

where $f_i$ is the normalised flux and $\Delta l_i$ is the width of the $i$th pixel

in rest-frame wavelength space. The associated errors are the formal errors in the sum and thus do not account for errors associated with continuum fitting.

#### 2.4.2 Measuring velocity profile uniformity

The apparent optical depth (AOD) method, as first described by Savage & Sembach [1991], offered an alternative way of measuring the column densities of velocity components in an absorber to more traditional Voigt profile analyses. The reader is referred to Prochaska [2003] for a discussion of the merits of each technique. Prochaska [2003] conducted a velocity bin based analysis of the chemical uniformity within DLAs by calculating the column density in each velocity bin using the AOD method. Here we will use the same technique to measure variation across the velocity profile of the absorber in both dust depletion (via Zn and Cr) and chemical uniformity (via Fe and Si) where possible. In particular we hope to show whether the dust depletion profiles are relatively uniform, or whether the dust is concentrated in one or two velocity components as this may indicate the presence of molecular hydrogen in the absorber (e.g. Ledoux et al. 2003).

Prochaska [2003] use unsaturated, unblended transitions such as Fe and Si and convert the flux pixels to optical depth pixels, binning the result in velocity space. These bins are not components in the traditional sense, but just velocity bins, as such they may contain one or more real velocity components. Nonetheless, if there is any non-uniformity across the absorption profile, it will still be reflected in the constructed velocity bins. Unlike Prochaska [2003] we will be applying this technique to blended transitions such as Zn and Cr. We circumvent the problem of line blending by binning the Voigt profile fits to the data, rather than the spectra themselves. The error in each pixel is still drawn from the actual spectral error array. This technique utilises the fact that we have multiple transitions of each blended element, which a straight-forward analysis of the data cannot account for. Using the error array corresponding to the flux in each pixel, rather than adapting the vpfit code to return the error associated with each pixel in the fit, will not underestimate the real error too greatly. This assertion can be verified by applying the technique to transitions such as Fe\(^{ii}\) and Si\(^{ii}\) which do not suffer from blending. A further advantage of using the Voigt profile fits to the spectra is that taking account of multiple transitions at different wavelengths makes the subsequent analysis more resilient to changes in bin size. That is, the effect of Root Mean Square (RMS) fluctuations in the data of an individual transition is reduced.

We will use 20\(\text{km s}^{-1}\) bins for our analysis, corresponding to eight 2.5\(\text{km s}^{-1}\) pixels per velocity bin; this gives reasonable SNR in each bin, whilst still providing enough bins to discuss the absorbers’ depletion properties. In practice the size of the bin does not alter our conclusions as the component-to-component dust depletions are resilient to changes in bin size; binning mainly effects the error bars in our analysis. We also performed the same analysis with the velocity bins offset by half a bin from the initial analysis to test whether the results were resilient to shifts in velocity space. We found this made no difference to our conclusions.

#### 2.4.3 Electron densities

The electron density of the gas can be constrained by the relative column densities of the neutral and singly ionised transitions of an element (e.g. Prochaska et al. 2006). For instance, under steady
state conditions and photoionization equilibrium the balance of photoionisation and recombination for Mg i and Mg ii gives

\[ n_e = \frac{N(\text{Mg})}{\Gamma(\text{Mg})} \frac{\alpha(\text{Mg})}{(\text{Mg}, T)} \]

where \(N\) are the measured column densities of the named transitions, \(\alpha(\text{Mg}, T)\) is the total recombination coefficient (radiative and dielectric) dependent on temperature, \(T\), and \(\Gamma(\text{Mg}) = \text{Const.} \times \sigma_{\text{ph}}(\text{Mg}) \times G/G_0\) represents the photoionisation rate of Mg i. \(\sigma_{\text{ph}}(\text{Mg})\) is cross-section to ionisation integrated over the incident radiation field and \(G_0 = 2.72 \times 10^{-3} \text{erg cm}^{-2} \text{s}^{-1}\) is the Habing constant \(\text{Habing},1968;\text{Gondhalekar et al,1996}\), where the factor of 1.7 is required to normalise \(G\) to the value of the Milky Way UV radiation field strength. A similar relationship can be derived for Fe i & Fe ii. Thus observations of the ratio of the column densities of a neutral and singly ionised species can constrain the electron density, \(n_e\), for a given strength of radiation field, \(G/G_0\). See Prochaska et al. (2000) Section 4.2 & Appendix D for details of the calculations. For our analysis we use the Fe i \(\lambda 2484\), Fe ii \(\lambda 2260, 2374,\) Mg i \(\lambda 2852\) and Mg ii \(\lambda 2803\) transitions. Note that for the ionisation of Fe i, H i charge transfer can dominate the transition, dependent on the exact ratio of \(n_{\text{HI}}\) to \(n_e\). If H i charge transfer does dominate then equation 2 will underestimate the true electron density. The results and conclusions drawn from observed limits on electron densities are dominated by measurements of Mg i and Mg ii (See Fig 5). Thus, the increased uncertainty in measurements of \(n_e\) based on Fe due to H i charge transfer will not effect any conclusions.

2.4.4 Constraints on absorber environment from velocity profiles

There have been extensive studies of the velocity profile structure in both DLAs and Mg ii absorbers. Early work focused on modeling DLAs as rotating discs of gas extending out from the associated galaxy Steidel et al. (2002). Later, more complex models including hot and cold rotational components, haloes and spherical accretion Prochaska & Wolfe (1997), Charlton & Churchill (1998) or outflows, such as super-bubbles expanding out into the Inter-Galactic Medium (IGM) Bond et al. (2003) were called upon to explain the increasingly complex Mg ii absorption profiles being observed and their sometimes highly symmetric velocity profiles. Given the paucity of strong Ca ii absorbers we do not have a statistical sample of absorbers required for a quantitative analysis, therefore we will restrict ourselves to a qualitative comparison with models from the literature. It will, nonetheless, be possible to place constraints on the physical environment of these absorbers such as whether they can be reproduced using simple disc models, outflows, etc.

3 RESULTS

Voigt profile fits for each absorber are shown in Appendix A whilst the unfitted Mg ii and Ca ii profiles are presented in Appendix B.

The measured column densities for all the absorbers in the sample are given in Table 3 whilst measured equivalent widths of Mg ii and Ca ii and the velocity width, as measured by \(\Delta v_{90}\) Prochaska & Wolfe (1997), are given in Table 4. The Ca ii transition in J1203+1028 is contaminated by sky absorption, but because the absorption features are not flat bottomed (i.e. not all the flux is absorbed) we are able to make a correction to the \(W^{934}\) measurement for the sky absorption as follows. The first step was to find

| Object | Rest-frame equivalent width [Å] | \(W^{934}\) | \(\Delta v_{90}\) [km s\(^{-1}\)] |
|--------|--------------------------------|---------|----------------|
| J004+4157 | 4.424 ± 0.003 | 0.966 ± 0.005 | 400 |
| J0256+0110 | 3.27 ± 0.01 | 0.39 ± 0.04 | 350 |
| J0334–0711 | 3.49–4.65\(^2\) | 0.31 ± 0.05 | 410 |
| J0407–4410 | 1.668 ± 0.002 | 0.282 ± 0.009 | 200 |
| J0517–4410 | 2.336 ± 0.002 | 0.346 ± 0.002 | 470 |
| J0830+2410 | – | 0.284 ± 0.007 | 190 |
| J0846+0529 | 2.22 ± 0.03 | 0.50 ± 0.03 | 160 |
| J0953+0801 | 0.408 ± 0.000\(^3\) | 0.34 ± 0.02 | 50 |
| J1005+1157 | 2.58 ± 0.02 | 0.78 ± 0.08 | 210 |
| J1028–0100 | (1.47 ± 0.08) | 0.29 ± 0.02 | 100 |
| J1107+0048 | 2.766 ± 0.009 | 0.34 ± 0.01\(^1\) | 190 |
| J1129+0204 | 2.11 ± 0.01 | 0.69 ± 0.03 | 170 |
| J1130–1449 | 1.794 ± 0.007 | 0.374 ± 0.005 | 120 |
| J1203+1028 | 2.58 ± 0.02 | 0.630 ± 0.006\(^4\) | 270 |
| J1211+1030 | – | 0.24 ± 0.01 | 330 |
| J1232–0224 | 2.071 ± 0.005 | 0.203 ± 0.007 | 120 |
| J1323–0021 | 2.156 ± 0.009 | 0.82 ± 0.02\(^2\) | 120 |
| J1430+0149 | 2.898 ± 0.009 | 0.30 ± 0.01 | 220 |
| J2328+0022 | (1.98 ± 0.07) | 0.250 ± 0.008 | 200 |

1 Reported measurement from Nestor et al. (2008)
2 Velocity structure too complex to separate Mg ii \(\lambda 2796\) and Mg ii \(\lambda 2803\). Therefore we measured the total equivalent width over both lines and assumed doublet ratios of 1:1 and 2:1 to calculate the range of possible \(W^{2796}\).
3 \(W^{2796} = 0.88 ± 0.05\) Å when measured in the SDSS DR4 spectrum of this quasar, thus it is included in the sample.
4 Corrected for sky absorption contamination, as discussed in Section 3, the associated error only includes the formal statistical error and is therefore an underestimate.

Table 4. Equivalent width and \(\Delta v_{90}\) measurements from high resolution spectra for each absorber in this work. The 1σ error in \(\Delta v_{90}\) is \(\lesssim 10\) km s\(^{-1}\), which is dominated by uncertainty in continuum fitting. Where no high resolution data exists the measurement from SDSS spectra are given in parentheses when available.

3.1 Depletions

The total column densities derived for Zn ii and Cr ii in Section 3 were used to calculate the depletion level in each of the absorbers. In high \(N_{\text{HI}}\) systems self-shielding ensures that the metallic elements considered here are predominantly in the lowest ionization state with an ionization potential less than 13.6 eV. Thus we may assume that the ratio of \(N_{\text{Cr}}/N_{\text{Zn}}\) is approximately equal to \(N_{\text{Cr}}/N_{\text{Zn}}\), i.e. no correction for ionization is required. Measured [Cr/Zn] ratios are given in Table B Fig. 1 shows the depletion in each of the systems versus \(W^{934}\) for each absorber. Included in the plot are the DLAs with known Zn ii, Cr ii and Ca ii absorption from Nestor et al. (2008) and Khare et al. (2004). For comparison we show the mean values of [Cr/Zn] vs. \(W^{934}\) measured statistically by WH06 from SDSS quasar spectra with Ca ii absorbers. The high \(W^{934}\) regime re-
Table 3. The ionic total column densities measured for each absorber in this work. Upper limits are quoted at 3σ significance. Systematic errors due to continuum level and component fitting are estimated at 0.03 dex. Quoted errors include random and systematic contributions added in quadrature.

| Object | Ca ii | Fe ii | Mg ii | Zn ii | Cr ii | Si ii | Al ii | Mn ii | Ti ii |
|--------|-------|------|------|-------|-------|-------|-------|-------|-------|
| J0334  | –     | 14.94 ± 0.04 | 12.84 ± 0.07 | 12.58 ± 0.09 | 13.19 ± 0.08 | –     | –     | 12.65 ± 0.04 | 11.9 ± 0.1 |
| J0517  | 12.74 ± 0.03 | 14.31 ± 0.03 | 12.74 ± 0.03 | 12.22 ± 0.04 | 12.53 ± 0.06 | 14.77 ± 0.03 | –     | 12.76 ± 0.03 | 12.21 ± 0.03 | <10.6 |
| J0846  | 13.06 ± 0.06 | 15.21 ± 0.04 | 12.96 ± 0.05 | <12.8 | <13.4 | –     | –     | 13.21 ± 0.06 | 13.00 ± 0.05 |
| J0953  | 13.57 ± 0.04 | 15.09 ± 0.04 | 13.24 ± 0.03 | 12.25 ± 0.06 | 13.17 ± 0.04 | 15.61 ± 0.07 | 15.31 ± 0.03 | 13.0 ± 0.7 | 12.1 ± 0.1 |
| J1005  | –     | 15.30 ± 0.05 | 13.10 ± 0.03 | <12.8 | <13.3 | –     | <13.5 | 13.03 ± 0.05 | <12.4 |
| J1107  | –     | 15.52 ± 0.03 | 13.00 ± 0.07 | 13.23 ± 0.04 | 13.83 ± 0.09 | –     | –     | 13.37 ± 0.04 | 13.12 ± 0.03 |
| J1129  | 13.11 ± 0.04 | 15.35 ± 0.03 | 13.14 ± 0.09 | 12.80 ± 0.05 | 13.66 ± 0.04 | 16.0 ± 0.5 | 13.81 ± 0.09 | 13.13 ± 0.04 | 12.79 ± 0.04 |
| J1203  | 13.05 ± 0.03 | 14.83 ± 0.03 | 12.99 ± 0.03 | 12.63 ± 0.06 | 13.38 ± 0.05 | –     | –     | 12.77 ± 0.05 | <11.2 |
| J1430  | 12.85 ± 0.04 | –     | 13.07 ± 0.05 | 12.94 ± 0.04 | 13.45 ± 0.04 | 15.75 ± 0.03 | 13.72 ± 0.03 | –     | 12.79 ± 0.04 |

1 Fe ii measured over full ∼ 800 km s⁻¹ range of absorber. \( N_{\text{gal}} = 14.25 ± 0.03 \) over ∼ 100 km s⁻¹ region which other elements could be measured.  
2 Si ii constrained by simultaneous fit to Si ii1526, 1808 and intervening Lyα forest.  
3 Mg i/2852 not covered by spectrum. Mg i column density derived from residual from Zn ii and Cr ii profile fits.

Figure 1. [Cr/Zn] vs. \( W_{3934} \) for each of the absorbers. The black diamonds show [Cr/Zn] measured in the UVES or HIRES spectra vs. \( W_{3934} \) measured from the SDSS spectra. An indication of the typical error is shown at the centre-top of the plot. The dashed grey regions show the average relation found by [WHPO05]. Other measurements of [Cr/Zn] for Ca ii absorbers in the literature are shown as black squares and asterisks ([Nestor et al. 2008; Khar et al. 2004]). The horizontal dashed black line shows the level of solar depletion. The vertical dashed grey line shows the \( W_{3934} \) equivalent width limit of our sample selection.

Figure 2. [Cr/Zn] vs. \( z_{\text{abs}} \) for the DLA from [Akerman et al. 2005] and each of the absorbers. The black diamonds show [Cr/Zn] measured in the UVES or HIRES spectra. The blue crosses show the DLA measurements of [Cr/Zn] whilst the blue triangles show upper limits to the depletion. The dashed black line shows the level of solar depletion.

Table 3 also shows several abundance ratios sensitive to dust depletion. It is evident that the depletion properties of these absorbers differ slightly from local measurements of the MW, LMC and SMC [Savage & Sembach 1996; Welty et al. 1999, 2001], whilst the [Zn/Fe] ratios in these Ca ii absorbers are similar to the warm halo phase in either the MW, LMC or SMC, the [Si/Zn] ratios are ∼ 0.5 dex higher than typically observed locally.

3.1.2 Depletion uniformity

Using the apparent optical depth method detailed in Section 2.4, we calculate the variation in [Cr/Zn] across the velocity profile in each absorber for which both Zn ii and Cr ii are detectable. The results are shown in Fig. 3.

There is little evidence for any significant (> 0.3 dex) deviation from uniform depletion across the velocity profile in each of the absorbers, even for those absorbers with reasonably broad velocity profiles (> 50 km s⁻¹; the exception is J0517~4410, to be discussed later). It is not necessarily surprising that an absorber with complex velocity structure might appear well mixed because velocity components do necessarily not reflect the spatial structure of the absorbing gas. 0.3 dex variation has 3σ significance at the SNRs of the spectra, thus the results in Fig. 3 restricts the range of dust depletion models which may apply to these Ca ii absorbers. In
Table 5. A table of abundance ratios in the absorber sample, relative to solar, traditionally used for assessing dust-depletion and chemical enrichment history. Solar abundances are taken from Lodders (2003).

| Object         | [Cr/Zn] | [Mn/Fe] | [Ti/Fe] | [Zn/Fe] | [Si/Fe] | [Si/Zn] | [Si/Ti] |
|---------------|---------|---------|---------|---------|---------|---------|---------|
| J0334−0711    | −0.4 ± 0.1 | −0.33 ± 0.06 | −0.5 ± 0.1 | 0.5 ± 0.1 | −     | −     | −     |
| J0517−4410†   | −0.71 ± 0.07 | −0.08 ± 0.04 | < −0.70 | 0.81 ± 0.05 | 0.44 ± 0.04 | −0.36 ± 0.05 | > 1.14 |
| J0846+0529    | −     | −0.02 ± 0.07 | 0.35 ± 0.06 | < 0.62 | −     | −     | −     |
| J0953+0801    | −0.10 ± 0.08 | −0.2 ± 0.7 | −0.5 ± 0.1 | 0.00 ± 0.07 | 0.45 ± 0.08 | 0.45 ± 0.09 | 0.9 ± 0.1 |
| J1005+1157    | −     | −0.30 ± 0.06 | < −0.39 | < 0.32 | −     | −     | −     |
| J1107+0048    | −0.4 ± 0.1 | −0.17 ± 0.06 | 0.17 ± 0.05 | 0.53 ± 0.06 | −     | −     | −     |
| J1129+0204    | −0.16 ± 0.06 | −0.26 ± 0.05 | −0.01 ± 0.05 | 0.29 ± 0.06 | 0.5 ± 0.5 | 0.2 ± 0.5 | 0.5 ± 0.5 |
| J1203+0128    | −0.27 ± 0.06 | −0.08 ± 0.06 | < −1.08 | 0.64 ± 0.07 | −     | −     | −     |
| J1430+0149    | −0.51 ± 0.06 | −     | −     | −     | −     | −     | −0.11 ± 0.05 | 0.34 ± 0.05 |

† Abundance ratios for this absorber based only on regions in velocity space where both transitions are detectable; in particular the Fe II transitions cover a much broader region of velocity space than most other transitions.

3.2 Chemical history

3.2.1 Enrichment history

We have detected both α-capture elements and Fe-peak elements in high resolution spectra of these Ca ii absorbers. α elements such as Si, Ca and Ti⁷ are created by type II supernovae on a timescale of < 2 × 10⁷ yr after a star formation event, whereas the Fe-peak elements are created by type Ia supernovae, which occur on a timescale of 10⁹ – 10⁷ yr. Thus, the ratio of α to Fe-peak elements can reveal something about the enrichment history and previous star-formation in the absorber (e.g. Wheeler et al. 1989; Dessauges-Zavadsky et al. 2007). Unfortunately the same element ratios are also affected by dust-depletion and disentangling the two effects is not trivial. However, if one observes enough different transitions it is possible to begin to separate the two effects (e.g. Herbert-Fort et al. 2008). Without a measurement of the metallicity of the absorber, a full deconstruction of the star-formation history of the absorber is not possible. Therefore, we follow the example of Herbert-Fort et al. (2006), presenting various abundance ratios which are instrumental in constraining the effects of dust-depletion and enrichment history in Table 5.

The abundance ratios measured in the sample of Ca ii absorbers are generally consistent with the DLA population (Prochaska et al. 2003). Furthermore, up to 0.33 dex variation is to be expected purely due to differential dust depletion in the sample, particularly for elements strongly affected by dust such as Ti (Savage & Sembach 1996; Dessauges-Zavadsky et al. 2006).

The Metal-Stong DLAs (MSDLAs) studied by Herbert-Fort et al. (2006) represent an unusual subset of DLAs and so we consider whether Ca ii absorbers overlap at all with these rare systems, as similarities between the populations may provide clues as to the physical origin of the absorbers. To classify an absorber as a MSLA, as defined by Herbert-Fort et al. (2006), requires N(Zn) ≥ 13.15 or N(Si) ≥ 15.95. Under this definition only two of the absorbers (J1107+0048 and J1129+0204) marginally classify as MSLAs. Similarly, Nestor et al. (2008) measure five of nine Ca ii absorbers to be MSLAs, although they are also all marginal cases. Therefore, with the caveat that the highest W⁹⁰ systems remain unprobed, the two populations are obviously not identical. Rather, it seems that the tail end of the Ca ii metal column density distribution overlaps with the definition of MSLAs. If some strong Ca ii absorbers arise, not because of sputtering of dust grains or weak ionisation backgrounds (see introductions of

⁷ Ti is not strictly speaking an α element, but it exhibits abundance patterns similar to other α-elements in Galactic stars (Edvardsson et al. 1995; François et al. 2004).
(a) The depletion profile across the $z = 0.59760$ absorber towards J0334$-$0711.
(b) The depletion profile across the $z = 1.02316$ absorber towards J0953$+$0801. The velocity profile for this absorber is too narrow to measure variation in $[\text{Cr}/\text{Zn}]$.
(c) The depletion profile across the $z = 1.14955$ absorber towards J0517$-$4410. There is evidence for significant variation, $\sim 0.3$ dex($3\sigma$), in the absorber's $[\text{Cr}/\text{Zn}]$ profile, consistent with findings of previous works (e.g. [Quast et al. 2008]).
(d) The depletion profile across the $z = 0.96497$ absorber towards J1129$+$0204. Mg $\lambda$2852 was not observed so the profile fits for Zn $\lambda$2026 and Cr $\lambda$2056 are less certain, making it difficult to assess profile uniformity.

**Figure 3.** Each top panel shows the Cr $\lambda$2056 transition, each middle panel shows the blended Zn $\lambda$2026 and Mg $\lambda$2026 transitions. The flux is shown as black histograms, the continuum as a dashed line (blue) and the fit to the Cr $\lambda$ or Zn $\lambda$ transition is shown as a solid line (blue). The dashed line (red) through the data shows the combined fit to Mg $\lambda$ and Zn $\lambda$. Each bottom panel shows the value of $[\text{Cr}/\text{Zn}]$ across the profile. The solid line (blue) represents the solar depletion level whilst the dot-dashed line (red) shows the total depletion measured in this absorber as referenced in Table 5 and Section 3.1.1. The black points are one set of 20 km s$^{-1}$ bins and the blue crosses are a different set of similarly sized bins, offset by 10 km s$^{-1}$ from the first. The value of $\chi^2$ given in the top left-hand corner of the panel is the $\chi^2$ per degree of freedom for the fit of the red dot-dashed line to the black points. That is, $\chi^2$ represents how well the profile is fit by a single depletion value.

WHP06; Zych et al. 2007) but simply because of large column densities of metals, this would be expected.

### 3.2.2 Chemical uniformity

Given the relative uniformity of the depletion profiles, as presented in Section 3.1.2, any variation in the $[\text{Fe}/\alpha]$ ratio (where $\alpha$ is any $\alpha$-capture element, such as Si, Ti or Ca) should be indicative of chemical non-uniformity in the absorbers, rather than variation in dust depletion. For the absorbers in our sample where we can measure $[\text{Fe}/\alpha]$ the results are presented in Fig. [4]. Even without metallicity measures it is possible to see abundance variations across the profile, which may indicate that different components of the gas have different enrichment histories. In the case that there is no similar variation in the $[\text{Cr}/\text{Zn}]$ ratio at the same velocities then the variation is most likely due to $\alpha$-enhancement.

The use of the unsaturated, unblended Fe $\lambda$ and Si $\lambda$ lines in this analysis also allows us to test the validity of using the fitted absorption profile, rather than the data themselves, to calculate the blended $[\text{Cr}/\text{Zn}]$ depletion profiles. We observe no significant $\lesssim 0.1$ dex difference to the derived [Fe/Si] ratios either when analysing the Voigt profiles fits or when analysing the data directly.

Only three absorbers have sufficient wavelength coverage to study their [Fe/Si] ratios and we comment on each in turn. J0953$+$0801 is not broad enough in velocity space to show signif-
(e) The depletion profile across the \(z = 0.74030\) absorber towards J1107+0048.

(f) The depletion profile across the \(z = 0.74630\) absorber towards J1203+1028. There is a blend with a \(z = 1.322\) C iv absorber at \(-110\) and \(-130\) km s\(^{-1}\).

(g) The depletion profile across the \(z = 1.24180\) absorber towards J1430+0149. There is a blend with a \(z = 1.933\) C iv absorber at \(-120\) km s\(^{-1}\).

Figure 3 – continued

significant variation across its profile. J1129+0204 shows a \(\sim 0.4\) dex (3\(\sigma\)) deficit of Si toward the left hand side of its profile (See Fig. 4(b)), however it has questionable significance; see discussion in Section 4.2. J0517+4410 also shows \(\geq 0.8\) dex (8\(\sigma\)) variation in its [Fe/Si] profile, but this variation is mirrored by its [Cr/Zn] profile (See Fig. 3(c)), which makes it likely the variation is a further signature of differential dust depletion, rather than \(\alpha\) enhancement.
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(a) The [Fe/Si] profile across the $z = 1.02316$ absorber towards J0953+0801.

(b) The [Fe/Si] profile across the $z = 0.74030$ absorber towards J1129+0204.

(c) The [Fe/Si] profile across the $z = 1.14955$ absorbers towards J0517−4410.

Note that the leftmost velocity feature seems to have a different chemical history to the rest of the profile. Given the [Cr/Zn] profile (see Fig. 3(c)) shows similar variation, the [Fe/Si] variation is likely an effect of dust depletion, rather than differential enrichment history.

Figure 4. Each top panel shows the Fe $\alpha$ transition, each middle panel shows the Si $\beta$ transition. The flux is shown as black histograms, the continuum as a dashed line (blue) and the fit to the Fe or Si transition is shown as a solid line (blue). Each bottom panel shows the value of [Fe/Si] across the profile. The short-dashed line (blue) represents the solar abundance ratio whilst the dot-dashed line (red) shows the total abundance ratio measured in this absorber as referenced in Table 5 and Section 3.2. The black points are one set of 20 km s$^{-1}$ bins and the blue crosses are a different set of similarly sized bins, offset by 10 km s$^{-1}$ from the first. The value of $\chi^2$ given in the top left-hand corner of the panel is the $\chi^2$ per degree of freedom for the fit of the red dot-dashed line to the black points. That is, $\chi^2$ represents how well fit the profile is by a single abundance ratio value. This absorption profile is too narrow to assess any signature of chemical non-uniformity.

3.3 Electron densities

Given the wavelength coverage of the spectra in our sample, there are two sets of transitions which can be used to constrain the electron density in each of our absorbers: Fe i λ2484 & Fe ii λλ2260, 2374 and Mg i λ2852 & Mg ii λ2803. It is not possible to measure an exact ratio for either set of transitions, just limits. Fe i is not detected at the SNR of the spectra, thus the measured $N$(Fe i)/$N$(Fe ii) ratio is an upper limit. Mg ii is saturated, thus the measured $N$(Mg i)/$N$(Mg ii) ratio is also an upper limit. Both ratios are derived using column densities measured via the AOD method (See Table 6 for results).

Using the AOD method ensures that the column densities for each transition are measured over the same velocity range, providing robust limits. For saturated pixels a minimum normalised flux is assumed of 0.05 or $\sigma$(flux)/5, whichever is greater; this provides a conservative lower limit to the optical depth. For each absorber we derive the product $n_e (G/G_0)^{-1}$ using a conservative estimate for the temperature, $T = 8000$ K, which maximises the recombination rates. Fig. 5 shows $n_e (G/G_0)^{-1}$ versus $W_0^{934}$ for each absorber. We take the limit from Fe or Mg, whichever provides the greatest constraint on $n_e$ in each case. Fig. 5 indicates that $n_e < 0.1$ cm$^{-3}$ in Cu ii absorbers if we assume $G/G_0 \sim 1$, as in the Milky Way. Thus, Cu ii absorbers are not comprised of extremely dense material since $n_{H}/n_{H} \sim 1$ atom cm$^{-3}$, unless the gas is extremely neutral ($n_{H}/n_{H} \lesssim 0.01$). Here we assume that the free electrons balance the ionized hydrogen, $n_e / (n_{H}/n_{H}) = n_{H}$.
3.4 Absorber environment

As detailed in Section 2.4.4, modelling absorbers as rotation discs or outflows, etc., allows us to predict the velocity structure of such gas. Thus, it is possible to constrain the physical environment of the absorber by ruling out mechanisms which cannot reproduce observed velocity structures. The velocity profiles of the Ca\textsc{ii} absorbers are shown in Fig. 6. Here we present any unsaturated transition with high SNR, such as Mg\textsc{i}\lambda2852 or Fe\textsc{ii}\lambda2374 from each absorber for comparison. There are a wide range of different profiles associated with Ca\textsc{ii} absorbers, so it is unlikely that a single physical process gives rise to the strong absorption; see Section 4.4 for further discussion.

4 DISCUSSION

4.1 Depletions

The Ca\textsc{ii} absorbers observed appear to have very similar depletion properties to the general DLA population (See Fig. 2). Whilst this similarity may at first seem contrary to the results of WHP06.
Table 6. The column density ratios of neutral-to-singly ionised species in the Ca ii absorber sample.

| Object       | N(Fe)/N(FeII) | N(Mg)/N(MgII) |
|--------------|----------------|---------------|
| J0044−4157   | <0.0004        | <0.0003       |
| J0256+0110   | <0.0008        | <0.0012       |
| J0334−0711   | —              | <0.0018       |
| J0407−4410   | <0.0003        | <0.0008       |
| J0517−4410   | <0.0007        | <0.0003       |
| J0830+2410   | <0.0010        | —             |
| J0846+0529   | <0.0041        | <0.0103       |
| J0953+0801   | <0.0013        | <0.0206       |
| J1005+1157   | —              | <0.0037       |
| J1028−0100   | <0.0018        | —             |
| J1070+0048   | <0.0009        | <0.0013       |
| J1129+0204   | <0.0005        | <0.0010       |
| J1130−1449   | <0.0007        | <0.0016       |
| J1203+1028   | <0.0159        | <0.0023       |
| J1211+1030   | <0.0009        | —             |
| J1232−0224   | <0.0029        | <0.0017       |
| J1323−0021   | <0.0006        | <0.0088       |
| J1430+0149   | —              | <0.0015       |
| J2328+0022   | <0.0011        | <0.0017       |

Figure 5. Upper limits on the product of the electron density $n_e$ and the near-UV radiation field $G$ scaled to $1.7 \times$ Habing’s constant $G_0 = 2.72 \times 10^{-3}$ erg cm$^{-2}$ s$^{-1}$, which roughly corresponds to the Galactic far-UV intensity Habing 1968 (Gondhalekar et al. 1980). The limits are established by our observed upper limits to the $N$(Fe)/$N$(FeII) and $N$(Mg)/$N$(MgII) ratios under the conservative assumption that the electron temperature is $T_e = 8000$K. Limits based on Mg are black, whilst those based on Fe are grey. The results indicate the Ca ii absorbers are not comprised of extremely dense material.

who find Ca ii absorbers to be amongst the most dusty absorbers known, Fig. 1 shows the results are consistent. Our observations only probed the lower $W_0^{3934}$ regime, which $\textbf{WHP06}$ find have much smaller levels of depletion. The distribution of points in Fig. 1 may suggest that the average depletions measured by $\textbf{WHP06}$ define a lower envelope to the dust depletions of Ca ii absorbers, rather than a simple linear correlation. That is, low $W_0^{3934}$ absorbers may comprise both weakly and strongly dust depleted systems, while high $W_0^{3934}$ absorbers may all be strongly dust depleted. Such a situation may point to two distinct mechanisms producing Ca ii absorbers.

The seven Ca ii absorbers for which we were able to measure the dust depletion properties across the velocity profile have variation $\lesssim 0.3$ dex (corresponding to $3\sigma$) in [Cr/Zn]. Once again, these dust depletion properties are consistent with results from the general DLA population ($\textbf{Prochaska} 2003$). Given the uniformity of the dust depletion it is unlikely that any of these absorbers harbour molecular hydrogen since we would expect the dust depletion to be concentrated into one or two components ($\textbf{Ledoux} et al. 2003$).

J0517−4410 is exceptional in its depletion variation, evident in both the [Cr/Zn] and [Fe/Si] profiles (See Figs. $\textbf{5C}$ & $\textbf{H(C)}$). Molecular hydrogen has been detected in this absorber at $z = 1.15079$ and 1.15085 ($\textbf{Reimers} et al. 2003$), which matches with the velocity bins exhibiting increased dust depletion. Note that narrow Ca ii absorption lines have also been detected at the same redshifts ($\textbf{Levshakov} et al. 2006$). It is possible that $H_2$ traces these neutral components, rather than dust as measured using Zn ii and Cr ii. Given that the AOD velocity bins would smear out the depletion signature, particularly in very narrow, cold components, the accuracy with which [Cr/Zn] traces $H_2$ or Ca ii cannot be assessed more precisely here. The abundance ratios from our analysis of J0517−4410 agree with the more detailed analysis of $\textbf{Quast} et al. (2008)$. The abundance ratios relative to Zn in this absorber match very closely the SMC abundances towards Sk 155 (group A) which are consistent with MW halo cloud abundance ratios ($\textbf{Weltz} et al. 2001$), except for [Si/Zn] ~ $0.36$ dex and [Ti/Zn] $< -1.9$, which are somewhat depleted. The significance of these differences is difficult to determine because analysis of the [Si/S] ratio along the line of sight to Sk 155 has shown that Si is more depleted toward Sk 155 than was apparent ($\textbf{Sofia} et al. 2008$).

The lack of evidence for molecular hydrogen from non-uniform dust depletion is seemingly at odds with the recent results from $\textbf{Nestor} et al. (2008)$ who use photo-ionisation modeling to show that Ca ii absorbers probably have total gas densities $> 1$ atom cm$^{-3}$ – the regime where we would expect molecular hydrogen to be present ($\textbf{Srianand} et al. 2005$). There is tentative evidence that stronger $W_0^{3934}$ systems should have larger total gas densities ($\textbf{Nestor} et al. 2008$), therefore the results presented here may just reflect the fact we have only probed the lower $W_0^{3934}$ regime and that it is the stronger $W_0^{3934}$ systems which are associated with molecular hydrogen. Another possibility is that we need to reassess some of the assumptions in the photo-ionisation modeling of $\textbf{Nestor} et al. (2008)$. For instance $\textbf{Nestor} et al. (2008)$ assume that the UV radiation field in the vicinity of their absorbers is similar to that of the solar neighbourhood; perhaps a more general range of UV fields needs to be considered (see Section 4.3).

4.2 Chemical history

Detailed analysis of the star formation history in Ca ii absorbers is not appropriate given the limitations of the spectra; a wider range of transitions, both Fe-peak and $\alpha$ elements, spanning a range of ionisation potentials, as well as observations of the H i column density to measure metallicities are required to conduct a full analysis of the star formation history. It is, nonetheless, possible to use the [$z$/Fe] ratio across the velocity profile to infer whether the gas in the absorber has multiple star-formation histories. Only two absorbers, J1129+0204 and J0517−4410, showed any variation in [Si/Fe] $\gtrsim 0.3$ dex ($3\sigma$ significance) across their profiles (see Figs. $\textbf{5B}$ & $\textbf{H(C)}$). Given that dust depletion can also cause variation in [Si/Fe] as well as differential enrichment history it is important to compare the [Si/Fe] and [Cr/Zn] profiles to break this degeneracy.

Recall that the dust depletion profile of J1129+0204
The [Fe/H] profile has \( \sim 3 \sigma \) significant deviation at \( \sim 25 \) km s\(^{-1}\). It appears that the components from \(-100\) to \(-25\) km s\(^{-1}\) may be offset in [Fe/H] from the components from \(-5\) to \(110\) km s\(^{-1}\). The apparent deviation is not significant given the a posteriori nature of the statistic. Only higher SNR data where all the individual bins between \(-100\) and \(-25\) km s\(^{-1}\) are \( > 3 \sigma \) from the mean can confirm whether this deviation is real. Such a deviation would be of interest because it is indicative of the gas having different star-formation histories. Possible explanations would include that the absorbing gas arises from the merging of two galaxies with different star-formation histories. Or we could be observing chemical inhomogeneities within a single galaxy; certainly our own Milky Way is observed to have variations in \( \alpha \)-enhancement (e.g. Nestor et al. 2007). Alternatively, we could be witnessing the building blocks of a galaxy coming together at \( z \sim 1 \). Such assessment must wait for higher SNR data however.

The [Fe/H] profile for J0517–4410 has \( \gtrsim 0.8 \) dex (8\sigma) deviation near \(-25\) km s\(^{-1}\) from an otherwise relatively uniform profile. Note, however, that a similar \( \sim 0.3 \) dex (3\sigma) deviation is seen in the [Cr/Zn] profile. Thus it is likely that this is purely a signature of dust depletion, rather than \( \alpha \)-enhancement in the absorber. Note that J0517–4410 is a sub-DLA with a strong ionising background (Quast et al. 2008) thus it is possible that \( N_{\text{FeII}}/N_{\text{CaII}} \neq N_{\text{FeII}}/N_{\text{Zn}} \) and some of the observed deviation in [Fe/H] and [Cr/Zn] could be due to variable ionisation. In addition, the trend in [Fe/H] with \( N_{\text{Si}}/N_{\text{Fe}} \) follows what one would expect if photo-ionisation were causing the variation. Nonetheless, across the region we have analysed here, the fraction of highly ionised to lowly ionised gas appears relatively constant (Quast et al. 2008); on-line material, thus it is likely the variation is due to dust depletion, rather than ionisation. This argument is strengthened by the fact that molecular hydrogen and \( \text{C}_1 \) are detected at the same velocities (See Section 4.3).

### 4.3 Electron densities

In Section 3.3 we show that the \( \text{Ca\,\,II} \) absorbers in our sample have \( n_e < 0.1 \) cm\(^{-3}\). This relies on the assumption that the radiation field in these absorbers is similar to or weaker than the radiation field of the Milky Way. Whilst in a few cases the radiation field may be greater than this, it seems unlikely to be the case in most absorbers as a stronger radiation field would lead to more highly ionized gas, thus this remains a robust upper limit. Note that the extragalactic UV background is about 10\times weaker in the far UV than the Galactic value (Sujatha et al. 2008) thus absorbers experiencing strong UV radiation fields must be associated with galaxies emitting a lot of energy in the far UV.

The electron densities and gas densities derived in Section 3.3 are within the range predicted by Nestor et al. (2008). Srianand et al. (2003) find molecular hydrogen to be associated with absorbers whose gas densities are \( n_\text{H} \gtrsim 1 \) atom cm\(^{-3}\), which is similar to the probable gas densities in the \( \text{Ca\,\,II} \) absorber sample derived in Section 3.3. \( n_\text{H} \sim 1 \) atom cm\(^{-3}\). Fig. 5 provides little evidence for greater gas densities at stronger \( W_{\text{3934}} \) as found by Nestor et al. (2008). However, we can only place limits on \( n_\text{H} \), rather than direct measurements so a detailed comparison is not possible. For instance, if stronger \( W_{\text{3934}} \) absorbers preferentially arise in stronger radiation fields for a given ionisation fraction, then Fig. 5 would imply greater \( n_\text{H} \) at higher \( W_{\text{3934}} \).

Three absorbers in our sample, those towards J0256+0110, J1107+0048 and J1323–0021, overlap with the absorbers modelled by Nestor et al. (2008). The cloudy models predict specific electron densities for each absorber: 0.050, 0.035, and 0.058 cm\(^{-3}\) for J0256+0110, J1107+0048 and J1323–0021, respectively (D. B. Nestor, private communication). Combining the electron densities measured by Nestor et al. with the limits on \( n_e (G/G_0)^{\text{3934}} \) derived in this paper we place lower limits on the radiation field strengths of 2.6\times, 1.6\times and 0.5\times (\( G/G_0 \)) in the absorbers towards J0256+0110, J1107+0048 and J1323–0021, respectively. Further measurements would be required to comment on whether there is a trend with \( W_{\text{3934}} \) and radiation field strength, though it is interesting to note that the weakest field is associated with the absorber with the highest \( W_{\text{3934}} \) of the three. Note that these are only rough estimates of the field strength as the electron densities measured by Nestor et al. depend on the strength of the radiation field used in the cloudy modelling. That is, running the cloudy models again with a different value for \( G/G_0 \) will result in a different value of \( n_e \) returned from the model, which in turn will lead to a new determination of \( G/G_0 \).

Generally Mg places stronger constraints on \( n_e \) than Fe in the spectra and, in any case, all the constraints are limits, so it is difficult to compare them with the measurements of Nestor et al. (2008). Constraining \( n_e \) and hence \( n_H \) more accurately might be achieved by spectral observations of the \( \text{C\,\,\,II} \) and \( \text{Si\,\,\,II} \) fine structure lines. However, note that these transitions constrain \( n_e \) more tightly if the gas is predominantly ionised (Prochaska 1999). Higher ionisation state lines such as \( \text{C\,\,\,IV} \) may arise in distinct regions and therefore not bear too directly on the \( \text{Ca\,\,II} \) absorbing gas.

### 4.4 Environment

Velocity structure by itself gives us limited insight into the true physical environments hosting \( \text{Ca\,\,II} \) absorption as we can reproduce the velocity profiles of all absorbers via various models in the literature (Recall Section 2.4.4). A further consequence of such models is that it is possible for multiple physical processes to produce similar velocity profiles. It is even possible to take a pathological line of sight through an outflow or inflow to reproduce what looks like a simple disc profile (e.g. Charlton & Churchill 1998). However, it is not possible for a pure disc model to reproduce an outflow-like profile because not enough high-velocity components are recovered from the model (e.g. Kacprzak et al. 2008). At a cursory glance it seems that the \( \text{Ca\,\,II} \) absorber sample has much greater velocity widths than the general DLA population; that is, they are less disk-like than general DLAs. Taking a sample of 95 DLAs with \( z > 1.6 \) based on observations from ESI, HIRES and UVES as described in Prochaska et al. (2003) we can measure their velocity widths using \( \Delta v_{90} \), as described by Prochaska & Wolfe (1997). We find that the median velocity width of such as sample is \( \Delta v_{\text{DLA}} \sim 75 \text{ km s}^{-1} \), whereas the \( \text{Ca\,\,II} \) absorber sample presented here has a median velocity width, \( \Delta v_{\text{CaII}} \sim 200 \text{ km s}^{-1} \) (See Table 4 for \( \Delta v_{90} \) measurements). Although we made no conscious decision to select high velocity width absorbers the \( \text{Ca\,\,II} \) sample is, in fact, biased due to the limit of detecting a 0.2 Å equivalent width feature at 4\sigma significance in SDSS spectra. The exact velocity cut this implies depends on the depth of the \( \text{Ca\,\,II} \) absorption and because we do not have this information for the DLA sample it is non-trivial to apply a cut to those data. For instance, a 0.6 Å equivalent width feature in a spectrum with SNR \( \sim 20 \) would require \( \Delta v_{90} \sim 120 \text{ km s}^{-1} \) to be detectable. Furthermore, if one...
the bulk of DLAs observed have absorbers consist of two populations, one which is due to a line-of-sight passing at low impact parameter through a quiescent galaxy, suggesting that we do not fully understand the relative importance of different physical mechanisms for producing absorbers. Nonetheless, most, if not all, Ca ii absorbers studied here are not simple disc-like systems as their Fe ii absorption line profiles are too complex (See Fig. 6).

5 CONCLUSIONS

In this work we present the first high resolution study of Ca ii-selected absorption systems, using spectra from the UVES and HIRES echelle spectrographs. We divided our analysis into three parts, examining the properties of dust, $\alpha$-enhancement and environment of the absorbers in turn, finding the following:

(i) We demonstrate for the first time the feasibility of using AOD methods on blended absorption profiles, such as Zn ii $\lambda 2062$ and Cr ii $\lambda 2062$, by utilising the Voigt profile fits, rather than the flux, which enables the assessment of velocity profile uniformity. We find, as previous authors (e.g. Prochaska 2003), that the AOD method is robust against binning size and positioning. Furthermore, we show there is little difference in applying the AOD to the fluxes compared to an absorption profile fit to the spectra, thus allowing us to use the method on blended lines. The Voigt profile AOD method allows us to combine the power of the more traditional Voigt profile fitting and the AOD methods when studying the absorber.

(ii) From a study of dust depletion across the absorber profile using the Zn ii and Cr ii transitions we conclude that the depletion in these absorbers is uniform at the 0.3 dex level, which corresponds to deviations < 3$\sigma$ in relative abundances at the SNR of the spectra. It is, therefore, unlikely that these absorbers harbour molecular hydrogen, as when H$_2$ is present the depletion is concentrated in one or two velocity components. The absorbers studied here have low $W_{3934}$ ($< 0.7$ Å), thus higher $W_{3934}$ absorbers may still trace H$_2$. These results are consistent with Prochaska et al. (2003), whose photoionisation modeling implied that only high $W_{3934}$ Ca ii absorbers should be associated with molecular hydrogen. If echelle observations of higher $W_{3934}$ systems fail to show evidence for molecular hydrogen then it may be necessary to reevaluate the assumptions behind the modeling of Nestor et al. (2008), such as the strength of the ionising UV background and the assumption of solar abundance ratios.

(iii) J0517−4410 stands out from the remainder of the absorber sample, exhibiting variation in dust depletion which may map to the detection of molecular hydrogen or C i in this absorber. The disadvantage of the AOD method is that binning in velocity space smears out the signal of dust depletion, precluding identification of the velocity components responsible. Thus it may be that the narrow C i and H$_2$ lines occur at the same velocities, whilst the broader Zn ii and Cr ii lines do not correspond to the same gas. Narrow components of Zn ii or Cr ii would be hidden by the broader absorption profile, so even a detailed Voigt profile analysis of this absorber would not illuminate the situation further. Furthermore, ionization effects on the measured variation in dust depletion across the profile may be important (Quast et al. 2008).

(iv) There are only a few systems where we can study the chemical uniformity of the absorbers by examining their [Fe/Si] ratios. J1129+0204 shows ~ 0.3 dex ($3\sigma$ significance) variation in its [Fe/Si] profile that is unlikely be explained by variable dust depletion, though at the SNR of the data this cannot be certain.

(v) The Ca ii absorbers studied here are not comprised of extremely dense material. Assuming a Milky Way-like radiation field there electron densities are, $n_e < 0.1$ cm$^{-3}$. Thus, unless the gas is very neutral ($n_{H}/n_{H_2} \lesssim 0.01$), $n_{H_2} \sim 1$ atom cm$^{-3}$. Comparing the three absorbers which overlap between our sample and that of Nestor et al. (2008), we find a range of UV radiation field strengths

![Figure 7. The measured $\Delta \nu_{90}$ distribution for the DLA sample of Prochaska et al. (2003), shown as the black histogram. The $\Delta \nu_{90}$ distribution for our sample of Ca ii absorbers is also shown as the hashed-grey histogram. The number of observed Ca ii absorbers is too small for a meaningful statistical comparison of the two populations. Given the $W_{3934}$ detection limit for Ca ii absorbers implies a cut in $\Delta \nu_{90}$, the two absorber populations could have the same intrinsic $\Delta \nu_{90}$ distributions. The approximate cut implied in $\Delta \nu_{90}$ at 150 km s$^{-1}$ is shown as a dotted vertical line (See discussion in Section 5.3).]
are likely in these Ca\textsc{ii} absorbers, from 0.5$\times$ to 2.6$\times$ the mean Galactic field strength.

(vi) We conclude that most, if not all, Ca\textsc{ii} absorbers studied here are not simple disc-like systems because they have complex, broad velocity profiles. Simulations only partially constrain the astrophysics of the observed velocity profiles of absorbers as multiple mechanisms can produce similar velocity profiles.

Whilst this work offers the first opportunity to examine Ca\textsc{ii} absorbers at high resolution, many questions as to the origin of these rare absorbers and the environments of their host galaxies remain unanswered. For further ground to be made in our understanding of Ca\textsc{ii} absorbers at high resolution, many questions as to the origin of these Ca\textsc{ii} absorbers and the environments of their host galaxies remain unanswered. For further ground to be made in our understanding of Ca\textsc{ii} absorption systems, future studies will require echelle observations of larger samples, including the, as yet unprobed, higher W\textsc{ii} systems as well as host galaxy Integral Field Unit (IFU) observations.

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Ca\textsc{ii} absorber environments

15
APPENDIX A: ABSORBER VOIGT PROFILE FITS

Here we present the Voigt profile fits to our absorption profiles for the absorbers and species listed in Table 3.

APPENDIX B: UNFITTED DATA

Here we present the Mg ii absorption line profiles which were not fitted (See Fig. B1). We also collate the observed Ca ii profiles into one figure as a comparative aid (See Fig. B2).

This paper has been typeset from a TEX/LATEX file prepared by the author.
Figure A1. Voigt profile fits to the $z = 0.59760$ absorber towards J0334−0711. A label (bottom-left) in each panel specifies the transitions incorporated in the profile fits to the spectral segment shown. The data are represented by the black histograms, whilst the continuum is the dashed line. The fit is shown as a solid line through the data. The residuals between the spectra and the fits, normalised by the 1σ error, are plotted above the spectra. Individual Voigt profile components are marked with ticks. In regions with blends the higher wavelength transition is marked with dashed ticks. The region representing $\Delta v_{90}$ is lightly shaded behind the data.

Figure A2. Voigt profile fits to the $z = 0.74294$ absorber towards J0846+0529, see Fig. A1 for description.
Figure A3. Voigt profile fits to the $z = 1.02316$ absorber towards J0953+0801, see Fig. [A1] for description.

Figure A4. Voigt profile fits to the $z = 0.83460$ absorber towards J1005+1157, see Fig. [A1] for description.
Figure A5. Voigt profile fits to the $z = 0.74030$ absorber towards J1107+0048, see Fig. A1 for description.

Figure A6. Voigt profile fits to the $z = 0.96497$ absorber towards J1129+0204, see Fig. A1 for description.
Figure A7. Voigt profile fits to the $z = 0.74630$ absorber towards J1203+1028, see Fig. A1 for description. Note there is a blend from an absorber at $z = 0.739$ in the Fe ii $\lambda 2374$ profile and blends from absorbers at $z = 1.32$ and 1.57 in the Cr ii and Zn ii $\lambda 2062$ profiles.

Figure A8. Voigt profile fits to the $z = 1.24180$ absorber towards J1430+0149, see Fig. A1 for description.
Figure A9. Voigt profile fits to the $\zeta = 1.14955$ absorber towards J0517–4410, see Fig. A1 for description.
Figure B1. The Mg\textsc{ii} absorption line structure in each of our absorbers with UVES or HIRES data with sufficient spectral coverage. The absorber’s quasar is identified in the top left-hand corner of each panel. The black histograms are the data and the red histograms are the associated error, whilst the adopted continuum is shown by the dashed line.

Figure B2. The Ca\textsc{ii} absorption line structure in each of our absorbers with UVES or HIRES data with sufficient spectral coverage. The absorber’s quasar is identified in the top left-hand corner of each panel. The black histograms are the data and the red histograms are the associated error, whilst the adopted continuum is shown by the dashed line.