Dusty Mg II absorbers: population statistics, extinction curves and gamma-ray burst sightlines

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ABSTRACT

We present a new determination of the dust content and near-ultraviolet/optical extinction curves associated with a sample of \( \approx 8300 \) strong, \( W_0^{\lambda 2796} > 1 \AA \), Mg II absorbers, redshifts \( 0.4 < z < 2.2 \), identified in Sloan Digital Sky survey (SDSS) spectra of quasars in the DR6 release. Taking into account the selection effects that result from dust extinction, including the reduction in the signal-to-noise ratio of an absorber appearing in a reddened quasar spectrum, we find a stronger dependence of \( E(B-V) \) on absorber \( W_0^{\lambda 2796} \) than in other published work. The dependence of the median reddening on \( W_0^{\lambda 2796} \) can be reproduced by the power-law model

\[
E(B-V) = \left(8.0 \pm 3.0 \times 10^{-4}\right) \times (W_0)^{3.48 \pm 0.3}
\]

for \( 1.0 \leq W_0 \leq 5.0 \). Observed Mg II samples, derived from flux-limited quasar surveys, are shown to suffer from significant incompleteness at the level of \( 24 \pm 4 \) per cent for absorbers with \( W_0 > 1 \AA \) and \( 34 \pm 2 \) per cent for absorbers with \( W_0 > 2 \AA \). Direct determination of the shape of the near-ultraviolet extinction curves, using high signal-to-noise ratio composites, for absorbers as a function of \( E(B-V) \) show evidence for systematic changes in the form of the extinction curves. At low \( E(B-V) \) (\( \lesssim 0.05 \)), the extinction curve is featureless and well represented by a Small Magellanic Cloud (SMC)-like extinction curve. For intermediate \( E(B-V) \)'s (\( \lesssim 0.2 \)), approximately a third of Mg II absorbers show evidence for a 2175 Å feature and an extinction curve similar to that of the Large Magellanic Cloud (LMC). For the small number of high \( E(B-V) \) (\( \gtrsim 0.3 \)) absorbers, the majority of which exhibit strong Ca II λλ3935,3970 absorption, there is evidence for the presence of a 2175 Å feature as strong as that found in the Milky Way (MW). Near-infrared photometry for six of the systems indicates that the rest-frame optical portion of the extinction curve for these high-\( E(B-V) \), and likely very high column density, systems is significantly greyer than the SMC, LMC or MW extinction curves. Application of the new results on the dust content of strong Mg II absorbers shows that dusty absorbers can account for a significant proportion, up to a factor of two, of the observed overdensity of absorbers seen towards Gamma-Ray Burst (GRB) sightlines, compared to sightlines towards quasars in flux-limited samples.

Key words: dust, extinction - galaxies: ISM - quasars: absorption lines - gamma-ray burst: general.

1 INTRODUCTION

Since the pioneering work of Bergeron (1986), Lanzetta & Bowen (1990, 1992) and Steidel et al. (1994) the presence of Mg II λλ2796,2803 absorbers in ‘haloes’ extending to distances of \( \sim 50-100 \) kpc about luminous galaxies has been well established. The more recent recognition of the importance of outflow, infall and feedback processes in general for our knowledge of galaxy evolution has reinvigorated attempts to understand the processes responsible for the existence of extended gaseous haloes associated with luminous galaxies.

Strong Mg II absorbers, Mg II λλ2796 rest-equivalent width (EW) \( \gtrsim 0.5 \) Å, seen in the spectra of background quasars reveal the presence of relatively cool, \( T \sim 10^4 \), ionised gas with neutral hydrogen column densities of \( \approx 10^{16-17} \) \( \text{cm}^{-2} \). The availability of very large samples of intermediate resolution, moderate signal-to-noise ratio (S/N) quasar

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spectra from the Sloan Digital Sky Survey (SDSS) (York et al. 2000), has allowed the compilation of extended samples of MgII absorbers (e.g. Nestor et al. 2005; Prochter et al. 2006; Quider et al. 2011) with consequent improvements in our knowledge of the statistical properties of the absorbers as a function of key physical parameters.

The homogeneity of the SDSS spectroscopy coupled with the quantitative nature of the quasar target selection (Richards et al. 2002) has also enabled progress to be made in quantifying the dust content of absorber populations at cosmological distances. Wild & Hewett (2005a) first demonstrated that the CaII λ3935,3970 absorption population, a subset of very strong MgII absorbers, showed evidence for the presence of dust with \(E(B-V)\) values as high as 0.2 magnitudes. The strong MgII absorber population as a whole shows much lower dust content, with mean \(E(B-V)\)≈0.02 (Wild et al. 2006; York et al. 2006). More recently, Ménard et al. (2008) quantified the dependence of the dust content of MgII absorbers as a function of both absorber EW and redshift.

Interest in the properties of dust associated with MgII absorbers has grown with the explicit linking of the absorber population to the star formation history of the galaxy population (Ménard et al. 2009) and the association between very strong absorbers and outflows (Bouché et al. 2007; Nestor et al. 2010). Dust has also been suggested as a possible explanation for the puzzling discrepancy between the increased incidence of MgII absorbers detected in Gamma-Ray Burst (GRB) compared to quasar sightlines (Prochter et al. 2006; Porciani et al. 2007).

In the local Universe the principal observable difference between dust extinction curves is the presence of the 2175 Å feature, the strength of which is inversely correlated with the increasing rise of dust extinction into the ultra-violet. The 2175 Å feature is strong within the Milky Way (MW) but only weakly detected within the Large Magellanic Cloud (LMC) and is practically absent within the Small Magellanic Cloud (SMC). The origin of the feature is generally believed to be aromatic carbonaceous materials, i.e. a mixture of Polycyclic Aromatic Hydrocarbon (PAH) molecules, which are abundant in the MW (Draine 2003; Wang et al. 2005). A few reports of the detection of a strong 2175 Å feature in individual absorbers have been made, e.g. Srianand et al. (2008) and Jiang et al. (2010) analysing two individual MgII systems each, Zhou et al. (2010) analysing a single extremely dusty object, and very recently Jiang et al. (2011), who report 39 detections. On the other hand, statistical studies of both CaII (Wild & Hewett 2005a) and MgII absorbers (Wang et al. 2005; York et al. 2006) favour SMC- or LMC-like extinction curves. Such studies to date have been characterised by modest sample sizes and the \(E(B-V)\) values of the absorbers are typically small, which means the limits on the presence of any sub-population of absorbers possessing MW-like extinction curves are not strong.

In this paper we employ a new, large, sample of MgII absorbers, derived using quasars contained in the SDSS DR6-release, to investigate the form of the rest-frame extinction curve associated with the absorber population with unprecedented accuracy. Adopting the approach of Wild et al. (2006), a full analysis of the presence of dust in the absorbers allows a quantitative determination of the selection biases that effect the observed MgII absorber sample. With such a quantification in hand we then review the implications of the selection biases on i) the redshift evolution of the dust content of MgII absorbers, ii) the redshift distribution of very strong MgII absorbers, and iii) the predicted number of MgII absorbers along GRB-sightlines.

The outline of this paper is as follows. In Section 2 we describe the quasar and MgII absorber catalogues which are used in Section 3 to estimate statistically the amount of dust in individual MgII systems. We also assess the effect of a dust bias on the completeness of the sample in Section 4. In Section 5 we show results of an investigation to identify the 2175 Å bump in the strongest MgII systems and we look at the correlations between absorber EW and redshift. We also discuss the implications of the results for MgII absorber statistics and the discrepancy in the observed frequency of absorbers along GRB- and quasar-sightlines in Section 5, before summarising our conclusions in Section 6. Throughout this work we assume a cosmology of \(\Omega_M = 0.3\), \(\Omega_\Lambda = 0.7\), and \(h = 0.7\).

## 2 QUASAR AND MgII ABSORBER SAMPLES

The base quasar sample consists of 91 665 objects, including 77 392 quasars in the Schneider et al. (2007) DR5 catalogue that are retained in the later DR7 quasar catalogue of Schneider et al. (2010). A further 13 081 objects are quasars, present in the additional DR6 spectroscopic plates, identified by one of us (PCH) using a similar prescription to that employed by Schneider et al. (2007), all of which are present in the Schneider et al. (2010) catalogue. An additional 1192 objects, which do not satisfy one, or both, of the emission line velocity width or absolute magnitude criterion imposed by Schneider et al. (2007), are also included. None of the results in the paper depend on the exact definition of the ‘quasar’-sample used.

The spectra are all processed through the sky-residual subtraction scheme of Wild & Hewett (2005b), resulting in significantly improved S/N at wavelengths λ>7200 Å and consequent increased detection efficiency for MgII absorbers at z>1.6.

The quasar sample is restricted to the redshift interval 0.5≤z≤3.5 and to objects with Galactic extinction corrected SDSS i-band magnitudes \(m_i \leq 19.1\), leaving 52 112 quasars. Broad Absorption Line (BAL) quasars identified by Gibson et al. (2009) or from our own BAL catalogue (Allen et al. 2011) are also excluded, leaving 48 587 quasars.

The presence of extended wavelength intervals without data in the SDSS quasar spectra is not ideal for the extinction estimation (Section 3). The sample is therefore restricted to essentially ‘complete’ spectra by the requirement that the number of valid pixels, \(NGOOD > 3500\), eliminating a further 490 quasars.

The final sample of 48 097 quasars is searched for MgII λλ2796.35, 2803.53 absorption doublets in the redshift interval 0.4≤z≤2.2. A ‘continuum’ is defined for each quasar via the application of a simple 61-pixel median filter. The ‘difference’ spectrum, to be searched for absorption features, is then obtained by subtracting the continuum from the original quasar spectrum. The absorption line search uses a matched-filter technique (e.g. Hewett et al. 1985) with two template Gaussian doublets of the appropriate
wavelength separation and full width at half maximum (FWHM) = 160 km s\(^{-1}\) (the resolution of the SDSS spectra), 200 km s\(^{-1}\) and 240 km s\(^{-1}\). Three values of the doublet ratio are incorporated into the search: 2:1 (corresponding to unsaturated lines on the flat part of the curve of growth), 1:1 (for saturated lines on the flat part of the curve of growth) and an intermediate case, 4:3. A further template with doublet ratio 1:1 and flat-bottomed absorber profiles, 380 km s\(^{-1}\) in extent, is also used to optimise the detection of very high EW doublets. At each pixel the template giving the minimum χ2 value is determined and candidate absorbers selected by applying a threshold value of S/N\(\geq 7\sigma\).

A total of 19 315 Mg\(\text{II}\) systems are identified but we confine our analysis to the sub-sample of 9 719 systems with EW of the 2796 Å line \(W_0^\lambda2796\)\(\geq 1\) Å. The left-hand panel of Fig. 1 shows the distribution of \(W_0^\lambda2796\) with the \(W_0^\lambda2796\)=1Å-limit indicated. The right-hand panel of Fig. 1 shows the redshift distribution for the \(\geq 1\) Å sample. Providing that any dust associated with the Mg\(\text{II}\) absorber population results in an extinction curve whose shape is not strongly dependent on \(W_0^\lambda2796\), the investigation presented here is not sensitive to the completeness of the absorber catalogue. However, the statistical properties of the absorber catalogue are in excellent agreement with previous work (Nestor et al. 2005). The catalogue is highly complete down to \(W_0^\lambda2796\)=1Å and, from a combination of visual inspection and investigation of the properties of other absorption species in ‘stacked’ Mg\(\text{II}\) systems, contamination by false detections is found to be <5 per cent.

There are 7 318 quasars with a single intervening Mg\(\text{II}\) absorber, 1 019 quasars with two absorbers and 116 quasars with more than two absorbers. Due to the increased uncertainty in the determination of the dust content of individual absorption systems in quasars containing multiple absorbers (i.e. > 2 systems), we chose to retain only quasars with single or double intervening Mg\(\text{II}\) absorbers. In the case of a double absorber we consider only the stronger system. The vast majority of double absorbers involve one or more low EW systems, however, we remove from the sample the 8/1019 spectra that possess two absorbers with an EW\(>2.5\) Å to leave a total of 8 329 systems. The results and conclusions derived in the paper are not sensitive to whether we use only single systems or single plus double systems.

3 MEASURING THE DUST CONTENT OF THE ABSORBERS

The presence of dust in an Mg\(\text{II}\) absorber affects the observed spectrum of the background quasar. The degree of reddening of a spectral energy distribution (SED) is described by an associated extinction curve, and the dust content is parameterised by a corresponding \(E(B-V)\)\(^1\) (e.g. Kinney et al. (1994)). The large and homogenous SDSS DR6 spectroscopic catalogue provides an opportunity to obtain estimates of the dust content for many thousands of absorbers. However, one must be sure that intrinsic quasar-to-quasar SED variations do not produce significant systematic biases in, or add significant scatter to, the \(E(B-V)\) determinations of the absorbers.

The population of Mg\(\text{II}\) absorbers is reported to have a mean dust content of only \(E(B-V)\simeq 0.02 - 0.03\) mag (Wild et al. 2006; York et al. 2006), which implies only small alterations to the shape of the SEDs of background quasars. Therefore, care must be taken to construct a quasar ‘control’ spectrum, which represents accurately the spectrum of an unabsorbed quasar. Such a spectrum then enables us to isolate the effect of dust in an absorber on the background quasar spectrum.

3.1 The control quasar spectrum

We have adopted an approach similar to Wild & Hewett (2005a) and York et al. (2006), which involves using the two-dimensional redshift, \(z\), versus magnitude, \(m_i\), plane to identify a sample of quasars from which to construct a control spectrum. The use of ‘neighbour’ quasars with similar redshifts in the control sample ensures that the wavelength coverage of control quasars is nearly identical to that of the target quasar, while also ensuring that the control sample quasars do not have systematically different (redshift dependent) SEDs. At fixed redshift the quasar apparent magnitude distribution is equivalent to the absolute magnitude distribution, \(M_i\). The large density of objects in the \(m_i\) versus \(z\) plane allows the control sample to be defined using

\(^1\) \(E(B-V)\) values refer to the absorber rest-frame unless specifically indicated otherwise.
3.2 Estimation of the median luminosity of the control quasars.

mismatch between the luminosity of the target quasar and that the control sample is not biased due to the systematic spectrum, rather than a fixed magnitude interval, means to the control spectra. SMC extinction curves, due to Pei (1992), and fit a curve of moved to the absorber rest-frame (Fig. 2).

The flux ratio spectrum for an absorber is calculated by dividing the quasar SED. The resulting flux ratio spectrum is then quasar rest-frame, removing, statistically, the signature of the target quasar spectrum by the control spectrum in the left-hand panel. The red line shows the best fitting SMC extinction curve, which corresponds to an $E(B-V) = 0.15$.

Magnitudes close to that of the target quasar, minimising the effect of any systematic magnitude-dependent SED changes.

The control spectrum was generated for each target quasar, by taking the median value (at each wavelength) of the 50 immediately brighter and 50 immediately fainter quasar spectra within a fixed redshift interval of $\Delta z = 0.1$ centred on the redshift of the target quasar\(^2\). The median was chosen instead of the mean, as it was less sensitive to flux outliers arising from intrinsic variation among quasar SEDs. A control spectrum is created for each of the 9,719 quasars with associated Mg\(\text{II}\) absorbers, but only quasars without a detected Mg\(\text{II}\) absorber are allowed to contribute to the control spectra.

Using a fixed number of quasars to define the control spectrum, rather than a fixed magnitude interval, means that the control sample is not biased due to the systematic mismatch between the luminosity of the target quasar and median luminosity of the control quasars.

3.3 Uncertainty in the $E(B-V)$ determinations

In order to test the accuracy of the method for calculating the $E(B-V)$ for a particular absorber\(^5\), we obtained estimates for the amounts of dust in a subsample of 4,550 quasar

$F(\lambda) = F_0 10^{-A(\lambda) V}$, \hspace{0.5in} (1)

to the flux ratio spectrum, where $A(\lambda)$ is the extinction at a particular wavelength given by $A(\lambda) = E(B-V) \frac{E_{\lambda-V}}{E_{B-V}} + R_V$, \hspace{0.5in} (2)

where $E_{\lambda-V}/E_{B-V}$ is given by Pei, and $R_V$ is the ratio of total to selective extinction. We have adopted $R_V = 3.0$, which is representative of the value in the MW and SMC\(^3\). $F_0$ and the reddening parameter $E(B-V)$ are left as free parameters in the fit, which is carried out using the non-linear ‘Levenburg-Marquardt’ algorithm (Marquardt 1963). The wavelength intervals corresponding to the strong telluric sky emission lines at $\lambda\lambda5578.5, 6301.7$, and to the prominent absorption lines\(^4\) of Fe\(\text{II}\), Al\(\text{I}\), Al\(\text{II}\), Mg\(\text{I}\), Ca\(\text{II}\), which may be present in the absorber spectrum, are excluded from the fit.

\(^2\) The 100 quasar spectra were shifted to the quasar rest-frame, and normalised over the wavelength interval common to all spectra. The median value at each rest-frame wavelength was then calculated.

\(^3\) The commonly adopted values of $R_V$ in the SMC and MW are 3.1 and 3.2 respectively (Fitzpatrick & Massa 2007). The shape of the extinction curve does not depend on the value of $R_V$.

\(^4\) The wavelengths of masked absorption lines are: Fe\(\text{II}(1527, 1608, 2250, 2261, 2344, 2374, 2383, 2587, 2601)\), Al\(\text{II}(1671)\), Al\(\text{II}(1855, 1863)\), Mg\(\text{I}(2853)\), Mg\(\text{II}(2796, 2803)\) and Ca\(\text{II}(3935, 3970)\). The mask consists of 10 Å wide intervals centred on the absorption lines.

\(^5\) A test of the method involved calculating $E(B-V)$ estimates for the sample of Ca\(\text{II}\) absorbers studied by Wild & Hewett (2005a) and no systematic differences with either redshift or $E(B-V)$ were found.

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\(\text{Figure 2. Left-hand panel: flux ratio as a function of wavelength for quasar SDSS J093508.37+271648.6, } z_{\text{qso}} = 0.94, \text{ with an Mg\(\text{II}\) absorber at } z_{\text{abs}} = 0.66. A ‘control’ quasar spectrum, representing the spectrum of the background quasar, is overlaid in red. Right-hand panel: flux ratio spectrum for the } z_{\text{abs}} = 0.66 \text{ Mg\(\text{II}\) absorber in the rest-frame of the absorber, obtained by dividing the quasar spectrum by the control spectrum in the left-hand panel. The red line shows the best fitting SMC extinction curve, which corresponds to an } E(B-V) = 0.15. \)
spectra with no identified absorbers from our quasar sample (Fig. 3). For the non-absorber quasar sample we create a simulated set of absorbers with $z_{abs}$ and $v_{abs}/v_{qso}$ distributions which are consistent with the corresponding redshift distributions in the absorber sample. We then obtain $E(B-V)$ estimates for this sample using the prescription in Section 3.2. The distribution is centred on $E(B-V) \approx 0.0$ indicating no detectable systematic bias in the determination of $E(B-V)$, with an encouragingly small uncertainty, $\sigma_{E(B-V)} \sim 0.025$, in the $E(B-V)$ estimates for individual quasars\(^6\). The spread arises from intrinsic quasar-to-quasar SED variations.

Notwithstanding the use of an individual control spectrum for each quasar, quasars with intrinsically unusual SEDs lead to flux ratio spectra still dominated by the variation among quasar SEDs. The presence of such variations in turn leads to poor determinations of $E(B-V)$. We have estimated the quality of fit of each absorber’s flux ratio with an extinction curve by using a Kolmogorov-Smirnov-like statistic. Our test uses the cumulative difference between the normalised best-fit extinction curve and normalised absorber’s flux ratio, to identify a systematic shape difference and thus poor-fit. The maximum cumulative difference, or $D_{\text{max}}$, is obtained for each absorber’s SMC, LMC and MW extinction curve fit. The $D_{\text{max}}$ distributions appear to show no evidence of significant bias as a function of absorber redshift, $E(B-V)$, EW and quasar magnitude (Fig. 4).

Visual inspection of quasar spectra with large values of $D_{\text{max}}$ reveals a mixture of quasars showing i) strong Fe II emission, ii) very blue continua or iii) red, but ‘flat’, spectra without the curvature expected due to conventional extinction curves. The number of such quasars is small, consistent with the tails of the distribution evident in Fig. 3, due to the small fraction of quasars with unusual intrinsic SEDs (unrelated to any signature due to intervening absorbers).

The 2σ uncertainty in $E(B-V)$ resulting from quasar-to-quasar SED variations corresponds to an $E(B-V)$ difference of 0.050 mag (Fig. 3). Such a difference produces a value of $D_{\text{max}}=0.04$ and we therefore define spectrum flux ratio fits with $D_{\text{max}}>0.04$ as possessing a poor fit to the SMC extinction curve. The number of such spectra (17/8329) represent an extremely small fraction of the total (0.2 per cent). We exclude such objects from further analysis until we consider the detailed shape of the MgII absorber extinction curves in Section 5.3.

The effectiveness of the $D_{\text{max}}$ statistic is verified by noting that the flux ratio spectra with multiple (> 2) absorption systems exhibit systematically larger values of $D_{\text{max}}$ than spectra with single or double absorbers. The differences are due to the presence of multiple extinction signatures at different redshifts, providing justification for the use of single and double absorber lines of sight only (Section 2).

## 4 DUST OBSCURATION BIAS

Extinction of quasar light due to the presence of dust in intervening absorbers, leads to objects being lost from magnitude-limited quasar surveys (Fall & Pei 1993; Wild et al. 2006). To illustrate the effect of extinction by intervening dust on our sample, the left-hand panel of Fig. 5 shows the observed extinction at 7500 Å (the effective wavelength of the SDSS $i$-band). Additionally, extinction due to an intervening absorber leads to a degradation of the spectrum $S/N$ and hence additional absorbers are lost from the sample, as their $S/N$ falls below the $7\sigma$ MgII absorber detection threshold (Section 2).

### 4.1 Extinction effect

We have used the magnitude and redshift distribution of the quasars in the quasar sample (Section 2) to obtain a probability that a quasar behind a dusty absorber will be lost from the sample. The presence of an absorber in a quasar spectrum leads to an extinction of quasar light $A_i$ (Fig. 5, left-hand panel). If the quasars in the sample\(^7\) were placed behind the absorber, objects fainter than 19.1 $- A_i$ will be

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\(^{6}\) It is necessary to modify how the quasar control sample is defined when we approach the extremes of the $m_i$ plane where there are not enough quasars to make up the control-spectrum using the scheme described in Section 3.1. In such a case we use the 100 quasars closest to the faintest/brightest quasar at a given redshift. The effectiveness of the modified sample definition is demonstrated by calculating $E(B-V)$ estimates for a sample of the 51st brightest quasars using control spectra defined using both the $\pm 50$ neighbouring quasars and the next 100 fainter quasars. Average differences in the $E(B-V)$ estimates of only 0.001 at the faint end and 0.0025 at the bright end, demonstrate that any systematic bias in the $E(B-V)$ estimates is insignificant.

\(^{7}\) We consider only absorbers that are displaced at least $\Delta z>0.1$ from the target quasar.
lost below the $m_i = 19.1$ flux limit. We can therefore quantify the probability an absorber of specified $E(B-V)$ and redshift is lost from the sample via

$$P_{\text{dust}} = 1 - \frac{N_{\text{qso}}(\leq 19.1 - A_i, z_{\text{abs}} < z_{\text{qso}} - 0.1)}{N_{\text{qso}}(\geq 19.1, z_{\text{abs}} < z_{\text{qso}} - 0.1)},$$

(3)

where $N_{\text{qso}}$ is the number of quasars satisfying the condition in brackets. An illustration of the bias calculation is shown in the right-hand panel of Fig. 5 for an absorber at $z_{\text{abs}} = 1.0$ with $E(B-V) = 0.125$.

### 4.2 Signal-to-noise ratio effect

For absorbers that remain within the sample there is a further reduction in the probability of detection due to the decrease in the $S/N$ of the quasar spectrum as the quasar becomes fainter because of the extinction from dust. Taking only the quasars that remain above the $m=19.1-A_i$ threshold determined above, we can determine how a quasar spectrum’s $S/N$ degrades for a given extinction $A_i$ by examining the median $S/N$ versus $m_i$ for the quasar spectra. Consider the effect of placing an absorber of specified $E(B-V)$ and redshift in front of a quasar with a given $m_i$, and hence $S/N$. The extinction due to the absorber makes the quasar fainter and the Mg II absorber may no longer be detectable given the reduced $S/N$ of the spectrum. An Mg II absorber will be lost from the sample when

$$S/N_{\text{qso}} \times \frac{S/N_{\text{qso,abs}}}{S/N_{\text{qso,absqso}}} \leq 7\sigma$$

(4)

holds true, where $S/N_{\text{qso,abs}}$ is the $S/N$ of the Mg II absorption feature, $S/N_{\text{qso,absqso}}$ is the degraded $S/N$ of the quasar spectrum, $S/N_{\text{qso,abs}}$ is the $S/N$ of the absorber’s target quasar spectrum, and $7\sigma$ is the Mg II absorber detection threshold. We can therefore obtain a separate probability that an absorber will be lost from the sample due to the reduction in the spectrum $S/N$,

$$P_{S/N} = 1 - \frac{N_{\text{qso}}(z_{\text{qso}} < z_{\text{qso}, \text{abs}}, z_{\text{qso}} \geq 7\sigma)}{N_{\text{qso}}(z_{\text{qso}} \geq 7\sigma)}.$$  

(5)

where $S/N_{\text{qso}}$ is the $S/N$ of a given quasar spectrum in the base quasar sample. $P_{S/N}$ is calculated using only the quasars that remain in the sample following the determination of $P_{\text{dust}}$ in Section 4.1.

### 4.3 Correcting the statistics

The base absorber sample is highly incomplete at large values of $E(B-V)$, and we provide a correction to the $E(B-V)$-distributions for both the extinction and $S/N$ effects described in this section. Each absorber is assigned an $E(B-V)$-weighting due to both obscuration effects according to

$$w = \frac{1}{1 - P_{\text{dust}}(E(B-V), z)} \times \frac{1}{1 - P_{S/N}(E(B-V), z)},$$

(6)

which allows the observed $E(B-V)$-distributions to be corrected. The weighting, $w$, becomes undesirably large for absorbers with large $E(B-V)$, where the probability an absorber is included in the sample is small. We therefore impose a conservative upper limit to the value of $w=6.67$, equivalent to the probability an absorber is included in the sample of 0.15. The multiplicative prescription for calculating $w$ is valid as we only apply the $S/N$ corrections to the population of absorbers which are not lost due to dust extinction effects. Thus, suppose we have a sample of absorbers from which 30 per cent of quasars fall below the magnitude limit due to extinction. The reduction in the $S/N$ is calculated for the remaining 70 per cent of quasars and (in the case that the $S/N$ effect reduces the number of absorbers...
by 10 per cent) the fractional completeness of the absorber sample is $0.7 \times 0.9 = 0.63$.

### 4.3.1 Accuracy of the corrected $E(B-V)$ estimates

The observed $E(B-V)$ distributions show a spread at fixed EW due in part to quasar-to-quasar SED-variations, quantified in Section 3.3 and illustrated in Fig. 3. In principle, a full deconvolution of the SED-induced variations could be undertaken using the observed $E(B-V)$ distributions to recover the intrinsic $E(B-V)$ distributions. However, such a procedure is both involved and unstable in portions of the $E(B-V)$ versus EW plane.

The use, in Section 5, of the median $E(B-V)$ values for the absorber population as a function of absorber EW already mitigates the impact of the intrinsic quasar SED-induced variations. However, the procedure described in the previous subsections does result in a small overestimation of the population median $E(B-V)$. The worst-case situation occurs when considering a population of absorbers with no dust, subject to the quasar SED-induced spread. A histogram of ‘observed $E(B-V)$’, exactly as shown in Fig. 3 is thus obtained. The observed median $E(B-V)$ is only a few thousandths of a magnitude from zero but, following correction of the $E(B-V)$ distribution according to Equation 6, the median $E(B-V)$ becomes +0.016 mag. The origin of the positive value derives in part to the small asymmetry to positive values in the histogram but (mostly) to the application of the correction scheme only to objects with apparently positive $E(B-V)$ values.

The overestimation of the median $E(B-V)$ is small under worst-case conditions and becomes much smaller as populations with dust-induced $E(B-V)$ are considered and the fraction of absorbers scattered artificially to negative $E(B-V)$ drops. Our conclusions in the paper, which derive from the presence of median $E(B-V)$ values $\gtrsim 0.07$ mag for absorbers with high Mg II EW, are essentially unaffected by the form of correction adopted to account for the small overestimation of the median $E(B-V)$ values. Results obtained after applying a uniform correction of +0.016 mag to all the median estimates and also no correction at all are not significantly different. We thus adopt a simple scheme that closely approximates the actual situation, applying a correction of +0.016 mag to the median $E(B-V)$ estimates of the absorber samples with Mg II EW $\leq 3.0$ Å and no correction to the median $E(B-V)$ estimates for Mg II EW $> 3.0$ Å.

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Figure 4. The Kolmogorov-Smirnoff-type $D_{\text{max}}$ statistic for the base sample of Mg II absorbers, fitted with an SMC-type extinction law, as a function of (top to bottom panels) absorber redshift, $E(B-V)$, equivalent width and quasar magnitude. The median points show no significant bias in the quality of fit as a function of any of the parameters. The horizontal line indicates the $D_{\text{max}}=0.04$ threshold, used to define systems with a ‘poor fit’ to the SMC extinction law.

Figure 6. Left-hand panel: Dust obscuration bias for SDSS quasar absorption systems as a function of absorber redshift ($z_{\text{abs}}$) and $E(B-V)$. The contours represent the probability that an individual absorber will not be observed. The dashed horizontal line represents the $E(B-V) = 0.15$ value which corresponds to a dust obscuration bias of 0.85 at $z_{\text{abs}} = 2$. In Section 5.2 we use this $E(B-V)$ value to define a conservative $E(B-V)$-cut to examine any statistical trends with redshift.
5 RESULTS

The amount of dust in Mg II absorption systems is generally found to increase as a function of the Mg II EW (York et al. 2006; Ménard et al. 2008). This increase has important implications for the understanding of galaxy evolution, as EW for the saturated Mg II absorbers measures the velocity spread in the gas (York et al. 2006) and there is a strong dependence of EW on the level of associated star-formation activity (Ménard et al. 2009).

5.1 Dust and absorber Equivalent width

The accuracy of the $E(B - V)_{\text{SMC}}$ estimate for each absorber was ensured by removing all spectra with a poor fit to the SMC extinction curve, i.e. $D_{\text{max}} > 0.04$ (Section 3.3). We chose the SMC curve as the average reddening properties of Mg II absorbers are found to be well characterised by an SMC-type extinction law (see Section 5.3).

10 To make the form of the extinction curve used to obtain $E(B - V)$ values explicit, where relevant, we use a subscript ‘LMC’, ‘MW’, ‘SMC’,... in the remainder of the paper

5.1.1 $E(B - V)$ Distributions

The dependence of dust content on Mg II EW is shown in Fig. 7. The median $E(B - V)_{\text{SMC}}$ is calculated for absorbers with EWs in the intervals 1.0-1.7 Å, 1.7-2.4 Å, 2.4-3.1 Å, 3.1-3.8 Å, 3.8-4.5 Å, and 4.5-5.0 Å. The equivalent median $E(B - V)_{\text{SMC}}$ values incorporating the bias corrections in Equation 7 are also shown. The error bars have been calculated using the ‘bootstrap’ method but, at low $W_0^{2796}$, the errors are limited by systematic uncertainties at the level of $\sim 0.005$.

The line in Fig. 7 corresponds to the best fitting power-law to the median bias-corrected $E(B - V)_{\text{SMC}}$ values of the form

$$E(B - V)_{\text{SMC}} = A (W_0^{2796})^\alpha,$$

where $A = (8.0 \pm 3.0) \times 10^{-4}$ and $\alpha = (3.48 \pm 0.3)$ and the model is applicable for $1.0 \leq W_0 \leq 5.0$ Å.

The number and distribution of objects evident in Fig. 7 with $E(B - V)_{\text{SMC}} < 0$ are consistent with the expected observational uncertainty in the $E(B - V)$ determinations (Section 3.3). A series of $E(B - V)_{\text{SMC}}$ distributions for different bins of mean Mg II EW 1.2 Å, 2.0 Å, 2.8 Å and 3.6 Å, are shown in Fig. 8.

5.1.2 Comparison with other work

Ménard et al. (2008) provide a parameterisation of the $E(B - V)$ content of strong Mg II absorbers as a function of EW that has started to see wide use in the literature (e.g. Eliaádottir et al. 2009; Sudilovsky et al. 2009). Ménard et al.‘s investigation presented observed-frame $E(B - V)_{\text{SMC}}$ distributions, which contrasts with the absorber rest-frame parametrizations, made possible by the direct use of the SDSS quasar spectra, presented here.

The observed-frame $E(B - V)_{\text{SMC}}$ dependence on Mg II absorber EW (equation 7 of Ménard et al.) can be related to our rest-frame $E(B - V)_{\text{SMC}}$ dependence via

$$E(B - V)_{\text{obs}} = E(B - V)_{\text{rest}} (1 + z)^{1.2}.$$ (8)

Fig. 9 shows our data in the $E(B - V)_{\text{obs}}$ versus EW plane (c.f. fig. 9 of Ménard et al.) along with the median $E(B - V)_{\text{obs}}$ points, median dust-corrected $E(B - V)_{\text{SMC}}$ values and the power-law fit (Equation 7), all transformed into the observed frame. There is good agreement between the Ménard et al. observed median $E(B - V)_{\text{SMC}}$ values and those determined here. However, our median dust-corrected $E(B - V)_{\text{SMC}}$ values lie significantly above Ménard et al.‘s observed values. The large differences can be ascribed to the ability to quantify the effects of $(B - V)$-bias on the observed Mg II sample, set out in Section 4. These dust obscuration effects while linked to EW, also become more pronounced at higher redshift.

5.2 Redshift evolution of $E(B - V)$

The ability to constrain how the dust content of Mg II absorbers varies with cosmic time, from 3.3 Gyr at $z = 2.0$ to 8.6 Gyr at $z = 0.5$, when a dramatic reduction in in the overall star formation rate density of the Universe (Hopkins 2004; Ménard et al. 2009) occurred, provides a significant constraint on models of galaxy evolution.
Figure 8. The $E(B-V)_{\text{SMC}}$ distributions of Mg II absorption systems for different equivalent width ranges. The solid line represents the distribution of observed $E(B-V)_{\text{SMC}}$-estimates, and the dotted line corresponds to the distribution corrected for bias (Section 4). The dotted lines represent estimates of the intrinsic $E(B-V)_{\text{SMC}}$ distribution, which exhibit more pronounced high-$E(B-V)$ tails.

Notwithstanding the quantitative corrections to the observed $E(B-V)_{\text{SMC}}$ distribution of the Mg II absorbers (Sections 4 and 5.1) the sample suffers from significant incompleteness for absorbers with large $E(B-V)$ at high redshifts. To investigate the evolution of the absorbers as a function of redshift we therefore confine our analysis to systems with $E(B-V)_{\text{SMC}} < 0.15$. The adopted limit to $E(B-V)_{\text{SMC}}$ corresponds to that of an absorber $P_{\text{dob}} > 0.85$ at the maximum absorber redshift, $z = 2.0$, employed (see Fig. 6).

5.2.1 Results and comparison with previous work

The restricted absorber sample ($E(B-V)_{\text{SMC}} < 0.15$) was divided into three redshift bins, with average redshifts of 0.77, 1.25, and 1.68. The resulting bias-corrected median rest-frame $E(B-V)_{\text{SMC}}$ are fit with a power-law of the form

$$E(B-V) \propto (1 + z)^\alpha,$$

where $\alpha = -0.2 \pm 0.3$, which shows no significant evolution with redshift. This determination is consistent with Ménard et al. (2008) who find a modest evolution of dust content with redshift ($\alpha = -1.1 \pm 0.4$).

While this analysis of the bias-corrected median points has deliberately been confined to absorbers with $E(B-V)_{\text{SMC}} < 0.15$ it is also possible to test whether the entire observed absorber sample is consistent with no evolution as a function of $z_{\text{abs}}$. Taking the bias corrected $E(B-V)_{\text{SMC}}$ distribution of absorbers in the low-redshift $\langle z_{\text{abs}} \rangle = 0.77$ slice we calculate the observed $E(B-V)_{\text{SMC}}$ distribution, by applying the inverse of the bias corrections to the $\langle z_{\text{abs}} \rangle = 0.77$ intrinsic distribution, centred on the higher redshift slices $\langle z_{\text{abs}} \rangle = 1.25$ and $\langle z_{\text{abs}} \rangle = 1.68$ respectively (Fig. 10). The resulting distributions for the higher redshift slices are consistent with the observed histograms, confirming the lack of evidence for significant evolution in the distribution of $E(B-V)_{\text{SMC}}$ with redshift.

5.3 Nature of the dust

Determining the nature of dust in Mg II absorption line systems is important as it provides a way to constrain the chemical evolution of galaxies over a range of cosmic time. Of particular interest is whether the strong $\sim 2175\text{ Å}$ feature observed in the spectrum of the MW is present in
our Mg II absorber sample. In general, the SMC extinction curve, rather than that of the MW, is found to best describe the average reddening properties of Mg II absorbers (Ménard et al. 2005; York et al. 2006; Ménard et al. 2008) with low $E(B-V)$. Taking advantage of the large sample of absorbers, and specifically the availability of a number of absorbers with low $E(B-V)$, we investigated the form of the extinction curve via construction of a composite spectrum and consideration of the properties of the absorbers with the very highest estimates of $E(B-V)$.

5.3.1 An optimal high-$E(B-V)$ composite absorber spectrum

Despite claims of being able to see evidence for the 2175 Å bump in single systems (Srianand et al. 2008), individual extinction curves have a low S/N. Using the much larger sample of absorbers presented here, we can combine a large number of extinction curves statistically, using an approach similar to Wild & Hewett (2005a), to improve the S/N and increase the sensitivity to the presence of any features.

An important consideration is the choice of which systems to combine. The optimum number of spectra to co-add is a trade-off between the number of spectra (in principle the more the better), and the median $E(B-V)$ of the coadded spectra (which favours a smaller number of spectra with the largest $E(B-V)$).

We also need to consider the goodness-of-fit of the spectra that will make up the composite spectrum, and so it was necessary to make a cut based upon the $D_{\text{max}}$ statistic (Section 3). However, it is conceivable that a system with a large SMC-$D_{\text{max}}$ value, and thus poor SMC fit, will in fact be well characterised by a MW extinction curve. We certainly do not want to remove such objects which exhibit a MW type dust signature from the composite sample. This $D_{\text{max}}$ discrepancy (between SMC and MW extinction curves) becomes more significant at higher $E(B-V)$ values, and we can quantify, for a given absorber redshift, the $E(B-V)_{\text{SMC}}$ value which corresponds to a poor-fit $D_{\text{max}} = 0.04$. We have determined how this $E(B-V)_{\text{SMC}}$ cutoff varies as a function of redshift and the results are shown in Fig 12.

Absorption systems in the shaded region of Fig 12, are those which satisfy the parameterised condition:

$$E(B-V)_{\text{SMC}} > a e^{-b z} + c$$

(10)

where $a = 38.7$, $b = 4.55$, and $c = 0.04$. For such absorbers, the form of the extinction curve, SMC or MW, can be determined via their SMC/MW $D_{\text{max}}$ statistics.
5.3.2 Results from the composite spectrum

We created a composite spectrum (Fig 13) from 211 objects satisfying the condition in Equation 10, by taking the mean\(^{12}\) flux value at each wavelength. Three further composites were created from the fitted extinction curves (SMC, LMC, MW) corresponding to each absorber. This allows for the characterisation of the type of dust by investigating whether the stacked spectrum is well fit by the SMC, LMC or MW curves. The resulting curves possess \(E(B-V)\) values of 0.12, 0.16, and 0.13 for the SMC, LMC and MW respectively. As predicted, Fig 13 shows that on average our carefully-selected high \(E(B-V)\) absorber subsample exhibits an extinction curve very similar to that of the SMC.

\(^{12}\) The mean (rather than the median) is now used to generate the composite spectrum to allow us to estimate the contribution of SMC-/LMC-/MW-type extinction to the composite.

We can quantify the significance of the SMC- versus LMC- and MW-type reddening by examining the relative contributions of SMC-, LMC- and MW-type dust to the composite spectrum in the region around the 2175 Å feature (Fig. 13-(bottom-right)). We obtain an estimate for the ratio of SMC-to-LMC-to-MW type spectra which contribute to our composite, by coadding a number of SMC, LMC, and MW extinction curves.
MW extinction curves and minimising the residuals$^{13}$ between the coadd and the composite spectrum (in the range 1900–2500 Å). Formally, we found that a combination of 137 SMC-, 74 LMC- and 0 MW-curves provides the best fit to the composite spectrum in the 2175 Å feature region. The best-fitting combination is shown in Fig. 13-(bottom-right). The analysis shows that of the absorbers which satisfy Equation 10, their extinction curves are well reproduced by a mix of SMC and LMC extinction curves in the ratio 65:35 with an uncertainty of $\pm 10$ in the ratio.

The existence of absorbers with LMC-type dust can be demonstrated more directly via consideration of Fig. 14, which shows the relationship between $D_{\text{max}}^{\text{SMC}}$ (x-axis) and both $D_{\text{max}}^{\text{SMC}}$ and $D_{\text{max}}^{\text{MW}}$ (y-axis) for the 211 absorber systems. In general, $D_{\text{max}}^{\text{SMC}} < D_{\text{max}}^{\text{MW}}$, which is to be expected if the majority of absorbers contain SMC- or LMC-type dust. Coadding the flux ratio spectra for the subset of 18 absorbers with $D_{\text{max}}^{\text{SMC}} > 0.02$ and $D_{\text{max}}^{\text{LMC}} < 0.02$ produces a composite flux ratio (Fig. 15) of which is closely reproduced by the LMC extinction curve. The mean $E(B-V)$'s for the SMC, LMC, and MW type extinction curves in this composite sample are 0.16, 0.21, and 0.18 respectively. It can be argued that the result must be true by construction, with individual objects chosen to possess LMC-like extinction curves. However, the procedure is no different from the identification of individual systems (Srianand et al. 2008, e.g.) from among large samples of quasar spectra (Srianand et al. 2008, e.g.). More convincingly, the 18 systems represent a significant minority of the base sample of 211. Furthermore, only a tiny fraction of absorption systems were eliminated from the sample via a $D_{\text{max}}$ threshold (Fig. 4) and it is very unlikely that unrelated intrinsic quasar-to-quasar SED variations are combining to reproduce a 2175 Å feature and overall shape that reproduces the form of the LMC-extinction curve to the accuracy shown in Fig. 15. The objects contributing to the composite are indicated in Fig. 11. With only half of these objects present in the restricted sample used to investigate redshift evolution (Section 5.2), it is not possible to say anything useful about the strength of the 2175 Å bump with redshift.

York et al. (2006) performed a statistical analysis of 809 MgII absorption systems from SDSS DR1, and searched for the 2175 Å feature in the dustiest 111 systems with an observed frame colour-excess$^{14}$ $\Delta (g-i) > 0.2$. They find an average $E(B-V)_{\text{SMC}} = 0.0805$ and no evidence of a MW dust signature in their composite spectrum. They also provide an estimate of the fraction of lines of sight that could have MW-type extinction, and provide an upper limit of 30 per cent.

Although we have reached a similar conclusion regarding the nature of dust, our sample of MgII absorbers is an order of magnitude larger, and we have created a composite

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$^{13}$ The squared deviations between the underlying composite spectrum and the coadded extinction curves.

$^{14}$ This excess corresponds to the difference between the actual colours of a quasar and the median colours of a quasar at that redshift.
Dusty Mg\textsc{ii} absorbers

Figure 14. $D_{\text{max}}$ for the SMC curve versus the $D_{\text{max}}$ for the LMC curve (red-points) and the MW curve (blue-points). The absorbers plotted are the 211 where discrimination between different extinction curves is possible according to the condition of Equation 10. The dashed lines represent the average poor-fit cut-off (Section 4) of $D_{\text{max}} = 0.04$. The circled objects are the two absorbers discussed by Srianand et al. (2008), which are found to contain signatures of the 2175 Å bump, and the solid box indicates objects which are very likely to contain bump signatures based upon their LMC/SMC $D_{\text{max}}$ statistic.

spectrum with a much larger average $E(B-V)_{\text{SMC}}$. The sample used has also been carefully constructed to ensure that only objects with accurate estimates of $E(B-V)$ (i.e. those with $D_{\text{max}}^{\text{SMC}} < 0.04$) are allowed to contribute to the composite. We provide a tighter constraint on the fraction of lines of sight with (the much less extreme) LMC-type extinction, as $35\pm10$ per cent, compared to York et al.’s upper limit of 30 per cent with MW-type extinction.

A recent study by Jiang et al. (2011) produced a catalogue of 39 candidate strong Mg\textsc{ii} absorbers, with EW $> 1$ Å and $1.0 < z < 1.86$, showing evidence for the presence of a weak 2175 Å feature. We find 19 of the Jiang et al. (2011) objects in our sample. All possess moderate $E(B-V)_{\text{SMC}} \sim 0.1$, and 15/19 satisfy the condition $D_{\text{max}}^{\text{SMC}} < D_{\text{max}}$. Jiang et al. (2011)’s highlighting of these absorbers adds further weight to the conclusion that a significant fraction of absorbers with intermediate $E(B-V)$ show evidence for the presence of a weak 2175 Å feature.

5.3.3 The dustiest absorbers and the shape of the extinction curve

Very few absorbers at cosmological distances with unambiguous 2175 Å features have been discovered. As discussed above, Srianand et al. (2008) find two Mg\textsc{ii} absorbers at $z \sim 1.3$, which are best-fit by LMC-type extinction, with $E(B-V)_{\text{LMC}}$’s of 0.27 and 0.36 respectively. Our analysis also finds these absorbers to be best-fit by LMC-type extinction, with corresponding $E(B-V)_{\text{LMC}}$’s of 0.30 and 0.36, consistent with their result. The two objects are present in our composite subsample and are indicated in Figs. 11 and 14. More recently, Jiang et al. (2010) find two Mg\textsc{ii} absorbers at $z \sim 1.4$, which may show detectable 2175 Å features. Our analysis finds the spectrum of SDSS J012147.73+002718.7 to be well fit by an LMC extinction curve with $E(B-V)_{\text{LMC}} = 0.17$, whereas the other spectrum (SDSS J145907.19+002401.2, henceforth J1459+0024), is best fit by the SMC curve with $E(B-V)_{\text{SMC}} = 0.31$. Jiang et al. find that J1459+0024 is not particularly well fit by any SMC, LMC or MW models because the extinction bump is much broader than that of the average LMC extinction curve. A detailed discussion of the shape of the extinction curve for J1459+0024, and the extinction curve of other high $E(B-V)_{\text{SMC}}$ objects is presented below.

Focussing on absorbers with comparable, or greater, estimates of $E(B-V)$, assuming an SMC-type extinction curve, there are 25 systems with $E(B-V)_{\text{SMC}} \geq 0.30$. Unsurprisingly, the majority of absorbers have relatively low redshifts, $z_{\text{abs}} \lesssim 1$, although a small number extend out to nearly $z_{\text{abs}} = 1.5$. Two of the systems are present in the sample of absorbers with detectable Ca\textsc{ii} absorption discovered by Wild & Hewett (2005a) and Wild et al. (2006). The most extreme system, with $E(B-V)_{\text{SMC}} = 0.60$, has been the subject of an earlier study. Zhou et al. (2010)’s fit to the SDSS spectrum and the broadband photometry from the UKIDSS survey (Lawrence et al. 2007) highlights the strength of the 2175 Å feature in the strong Mg\textsc{ii} absorber, at $z_{\text{abs}} = 0.884$, which shows extremely strong Ca\textsc{ii} absorption, although they do not note the connection to the Ca\textsc{ii} absorber population. Employing constraints on the shape of the extinction curve extending to the rest-frame near-infrared, provided by $JHK$ photometry from 2MASS (Skrutskie et al. 2006), Zhou et al. (2010) present an extinction curve using the parametrization of Fitzpatrick & Massa (2007). The form of the curve includes a very strong 2175 Å feature, superposed on a rather greyer background compared to any of the SMC, LMC or MW extinction curves. Zhou et al. (2010)’s fit to the SDSS spectrum and the broadband photometry leads to a smaller value of $E(B-V) = 0.28$ but with a relatively large value of $R_V = 3.87$.

Using our full sample of 25 objects with $E(B-V)_{\text{SMC}} \geq 0.30$, it is possible to gain further insight into the shape of the extinction curve associated with the dustiest intervening absorbers. Table 1 provides a summary of information for the 25 systems and the background quasars, including $YJHK$ photometry from the UKIDSS survey (Lawrence et al. 2007) where available. The population is not significantly influenced by the effects of extinction from two or more absorbers along the line of sight to a quasar. An extensive search for strong absorbers, including the Fe\textsc{ii} line complexes at $\lambda 2344.2$ and $\lambda 2586.7$, covering the redshift interval $0.36 < z < 2.88$, shows six of the quasars possess two absorbers with $W_{\lambda 1216}^{\text{abs}} > 1.0$ Å, whereas three are expected by chance.

A striking feature of the absorption line spectra is the almost ubiquitous presence of Ca\textsc{ii} $\lambda 3934.8, 3969.6$ absorption. Fourteen of the 23 absorbers with $z_{\text{abs}} < 1.31$, where Ca\textsc{ii} lies within the SDSS spectra, individually show evidence for Ca\textsc{ii} absorption and a median composite of the 23 absorbers shows a rest-frame EW of Ca\textsc{ii} $\lambda 3934.8 = 0.38 \pm$
0.05 Å. The absorption systems are thus closely related to the (observationally) rare, dusty CaII absorber population identified by Wild & Hewett (2005a), the properties of which are discussed by Wild et al. (2006, 2007). The presence of strong absorption due to a species that is so strongly depleted onto dust as CaII is most naturally explained by the presence of very large gas columns (Wild et al. 2006) and our interpretation is that these absorbers will possess hydrogen columns as large as DLAs.

Using a model unreddened quasar spectrum (Maddox et al. 2008) we essentially confirm the results of Zhou et al. (2010) for the shape of the extinction curve for the absorber in SDSS J100713.68+285348.4. It is possible to undertake an identical analysis for the six additional absorbers that possess YJHK photometry. In all cases, adopting our $E(B-V)$ values (using any of the SMC, LMC or MW curves) from the SDSS spectra produces predictions that are grossly inconsistent with the SDSS ($i$-band) to YJHK colours. Specifically, compared to any of the SMC/LMC/MW-extinction curves, the shape of the extinction curve probed by the SDSS spectra of the absorbers at redshifts $z_{abs}$ $\approx$ 0.75 (rest-frame wavelengths $\approx$ 2100-5000 Å) is much steeper than the curve at rest-frame wavelengths $\approx$ 4500-14000 Å probed by the broadband $i$ to $K$ colours. In other words, the extinction curve is significantly greyer at $> 5000$ Å, with local extinction curves predicting a median $i-K$ colour 0.72 mag redder than that observed for the six absorbers.

While the five-parameter parametrization of Fitzpatrick & Massa (2007) would provide accurate fits to the SDSS spectra and the $i$ through $K$ photometry of the six absorbers, we chose to adopt the established one-parameter family of extinction curves presented by Fitzpatrick (1999), in which the shape of the untraviolet to near-infrared extinction curves depends on the value of $R_V$ (see fig. 7 of (Fitzpatrick 1999)).

We find satisfactory fits to both the flux ratio spectra derived from the SDSS quasar spectra and the YJHK broadband photometry of the six objects using a Fitzpatrick (1999) curve with $R_V$ $= 2.1$ (see Appendix A). The $D_{max}$-statistic distribution is as good as that from any of the SMC, LMC, MW or Zhou et al. extinction curves. The median $i-K$ colours (model - observed) using the Fitzpatrick and Zhou curves are +0.09 mag and -0.04 respectively (cf. the +0.72 value using any of the SMC, LMC or MW curves). Individual YJHK magnitudes are reproduced to the level of $\sigma$ $\approx$ 0.12 mag using either the Fitzpatrick or Zhou curves but with some differences reaching 0.3 mag. The small number of absorbers, combined with the effects of intrinsic quasar variability (between the epochs of the SDSS and UKIDSS photometry) and object to object SED variation, preclude the generation of more exact constraints on the form of the extinction curve but the need for a significantly greyer shape in the near-ultraviolet and optical is clear.

The inferred values of $E(B-V)$ for the six systems employing the Fitzpatrick $R_V$ $= 2.1$ curve are given in Table 1. We note that the form of the Fitzpatrick $R_V$-dependent extinction curves at low values of $R_V$ reproduces the shape of the extinction curve in the near ultraviolet with a 2175 Å feature of strength comparable to that in the MW, combined with a somewhat steeper increase in extinction with decreasing wavelength, a key feature of the behaviour found by Fitzpatrick & Massa (2007). From the data available, it is not possible to conclude whether Zhou et al. (2010)’s modeling, employing a super-strong 2175 Å feature, or the $R_V$-dependent form (with an extreme value of $R_V$ $= 2.1$) of Fitzpatrick (1999), is superior but the simple one-parameter-dependent form, with a 2175 Å feature of constant strength, is attractive. In the Appendix we provide both a graphical representation of the extinction curve and quantitative values of $E(\lambda-V)/E(B-V)$ as a table.

The difference in the form of the extinction curve (from SMC/LMC/MW curves) for absorbers with high $E(B-V)$, including the likely presence of a strong 2175 Å feature, raises the question of whether there is a systematic dependence of the extinction curve shape with $E(B-V)$. While the detection of the 2175 Å feature in individual spectra with small $E(B-V)$ is not viable, the prevalence of an SMC-like curve for absorbers with low extinctions ($E(B-V)$ $\leq$ 0.05) is unambiguous; any extinction curve with a 2175 Å feature as strong as that in the MW can be ruled out with confidence (Fig. 16). For absorbers with intermediate $E(B-V)$ $\approx$ 0.15 we find evidence for the presence of a weak 2175 Å feature in a significant fraction of systems (Section 5.3.2). The results for systems with larger $E(B-V)$ require confirmation using a much larger sample of absorbers with near-infrared photometry but for the first time there is an indication of a strong systematic change in the form of the near-ultraviolet to near-infrared extinction curve as a function of $E(B-V)$, with the shape of the curve in the dustiest systems differing from any of the standard curves in the local Universe.

### 5.4 Implications for MgII absorber statistics

The quantitative dust-dependent bias, formulated in terms of the absorber $E(B-V)$, derived in this paper has significant implications for the study of the MgII absorber population. Fig. 17 shows the distribution of observed EW and redshift for our absorber sample. Also shown are the bias-corrected distributions, calculated using the object by object bias-corrections (equation 6). A significant fraction of absorbers are missing from the sample, 24 ± 4 per cent for absorbers with EW $>$ 1.0 Å in the redshift interval 0.4 $< z < 2.2$. The missing fraction rises to 34 ± 2 per cent for absorbers with EW $>$ 2.0 Å. The formal errors on the incompleteness fraction are at the level of 1 per cent and the error is dominated by the systematic uncertainty associated with the $dc$ offset (Section 4.3.1). The systematic uncertainty becomes less significant for the EW $>$ 2.0 Å sample.

Nestor et al. (2005) find the the EW distribution of a sample of 1,300 absorbers (with redshifts 0.366 $\leq z \leq 2.269$) from SDSS DR4 is well described by an exponential distribution. They find that although moderately strong lines (0.4 Å $< W_{2750}^\lambda < 2.0$ Å) show no evidence for redshift evolution, the absorbers with larger EWs show an increase in number with redshift that is more pronounced for ab-
Dusty Mg II absorbers

Figure 15. The flux ratio against wavelength for a composite mean spectrum created from 18 objects satisfying Equation 10. The absorbers have been chosen (using the $D_{\text{max}}$ statistic) as those most likely to exhibit LMC-type dust. The underlying composite spectrum is best fit by the LMC composite extinction curve, with mean $E(B-V)_{\text{SMC}} = 0.16$, $E(B-V)_{\text{LMC}} = 0.21$ and $E(B-V)_{\text{MW}} = 0.18$.

Figure 16. The flux ratio against wavelength for a composite median spectrum created from 1792 absorbers with $0 \leq E(B-V)_{\text{SMC}} \leq 0.05$ and $z_{\text{abs}} > 0.9$. The shape of the flux ratio spectrum for the low $E(B-V)$ composite is consistent with SMC-type extinction with median $E(B-V)_{\text{SMC}} = 0.018$, $E(B-V)_{\text{LMC}} = 0.022$ and $E(B-V)_{\text{GAL}} = 0.016$. The minimum flux ratio on the y-axis has deliberately been set to 0.84 and the x-axis extended to 4100 Å to better show the shape of the extinction curve at small deviations from unit flux-ratio. A composite based on the mean flux-ratio for the sample is noisier but extremely similar in shape.

sorbers of higher EW. Nestor et al. interpret this redshift dependence as an evolution in the kinematic properties of absorbers over a range of intermediate redshifts. Lundgren et al. (2009) find a similar result which suggests stronger evolution in the redshift number density of strong Mg II absorption systems relative to lower EW samples, albeit over a smaller redshift range $0.4 < z < 0.8$.

Using our parametrized dust correction (equation 7), we predict that the observed relative fraction of high EW systems will decrease by 36 per cent over the redshift interval $0.4 < z < 2.0$. Our results thus predict that the true increase in the proportion of high EW systems with increasing redshift is significantly greater than found by Nestor et al. (2005) from the observed population of absorbers.

5.5 The GRB/Quasar absorber number density sight line discrepancy

We have discussed the effects of dusty high EW absorbers on the completeness of optical magnitude-limited quasar samples over a range of absorber redshifts. The highest redshift absorbers have been observed using GRB optical afterglows as background sources (Olivares et al. 2009). Although GRBs would individually experience the same obscuration effects, GRBs are found to have a huge range in intrinsic brightness and spectra are obtained at variable time intervals following the GRB’s peak brightness. The consequent very large dispersion in apparent GRB brightness, rather than the presence of modest amounts of dust in any inter-
Table 1. A sample of 25 objects with $E(B - V)_{\text{SMC}} > 0.3$

| SDSS name                  | $z_{\text{qso}}$ | $z_{\text{abs}}$ | $W_{2796}^{\text{32796}}$ (Å) | $E(B - V)_{\text{SMC}}$ | $E(B - V)_{\text{Fitz}}$ | $i_{\text{AB}}$ | $Y_{\text{Vega}}$ | $J_{\text{Vega}}$ | $H_{\text{Vega}}$ | $K_{\text{Vega}}$ |
|----------------------------|------------------|------------------|-------------------------------|-------------------------|------------------------|----------------|-----------------|----------------|----------------|----------------|
| J081524.62+55153.3         | 1.781            | 1.323 (1.608)    | 1.9 (1.3)                     | 0.37                    | 0.31                   | 18.63          | ---             | ---             | ---             | ---             |
| J083257.64+333214.6        | 1.017            | 0.716            | 2.2                           | 0.33                    | 0.29                   | 19.06          | ---             | ---             | ---             | ---             |
| J085244.74+343540.4        | 1.656            | 1.310 (0.884)    | 3.1 (2.5)                     | 0.31                    | 0.27                   | 18.21          | ---             | ---             | ---             | ---             |
| J091753.89+000300.8        | 2.139            | 0.729            | 4.3                           | 0.34                    | 0.31                   | 18.78          | 17.92           | 17.46           | 16.69           | 15.84           |
| J092053.12+385020.7        | 1.276            | 0.472            | 1.8                           | 0.30                    | 0.28                   | 17.96          | ---             | ---             | ---             | ---             |
| J092339.29+595747.8        | 0.839            | 0.662            | 2.6                           | 0.31                    | 0.28                   | 19.02          | ---             | ---             | ---             | ---             |
| J093444.30+172435.5        | 1.899            | 0.553            | 2.8                           | 0.33                    | 0.32                   | 19.00          | ---             | ---             | ---             | ---             |
| J093738.04+562838.9        | 1.804            | 0.978            | 4.9                           | 0.30                    | 0.23                   | 18.50          | ---             | ---             | ---             | ---             |
| J100713.68+285348.4        | 1.050            | 0.884            | 3.5                           | 0.60                    | 0.50                   | 18.25          | ---             | ---             | ---             | ---             |
| J113152.15+435318.3        | 2.139            | 1.098 (1.377)    | 2.4 (1.1)                     | 0.34                    | 0.28                   | 18.82          | ---             | ---             | ---             | ---             |
| J13811.59+382119.5         | 0.899            | 0.759            | 1.9                           | 0.44                    | 0.38                   | 18.41          | ---             | ---             | ---             | ---             |
| J120301.00+063441.5        | 2.180            | 0.862            | 5.6                           | 0.42                    | 0.37                   | 18.44          | 17.28           | 16.98           | 16.41           | 15.51           |
| J120913.61+433920.9        | 1.397            | 0.412            | 2.4                           | 0.30                    | 0.28                   | 17.35          | ---             | ---             | ---             | ---             |
| J121547.11+294099.9        | 1.532            | 0.788            | 1.0                           | 0.30                    | 0.25                   | 17.88          | ---             | ---             | ---             | ---             |
| J124946.59+124000.0        | 1.688            | 1.469            | 2.3                           | 0.33                    | 0.31                   | 18.20          | 16.90           | 16.28           | 15.49           | 15.07           |
| J131103.19+551354.3        | 0.927            | 0.600            | 1.2                           | 0.39                    | 0.37                   | 18.87          | ---             | ---             | ---             | ---             |
| J133751.11+052746.2        | 1.743            | 0.575            | 1.4                           | 0.31                    | 0.30                   | 17.99          | ---             | ---             | 16.05           | 15.72           |
| J140807.05+474457.3        | 1.497            | 0.776            | 3.0                           | 0.30                    | 0.25                   | 18.61          | ---             | ---             | ---             | ---             |
| J144611.68+484613.7        | 1.202            | 0.669            | 2.2                           | 0.38                    | 0.34                   | 18.46          | ---             | ---             | ---             | ---             |
| J144621.42+012552.4        | 1.422            | 0.525 (0.510)    | 2.4 (1.4)                     | 0.34                    | 0.32                   | 18.08          | 17.48           | 16.92           | 16.13           | 15.71           |
| J145344.23+102557.5        | 1.770            | 0.757            | 2.6                           | 0.38                    | 0.34                   | 19.02          | 18.09           | 17.66           | 17.10           | 16.40           |
| J145907.19+002401.2        | 3.037            | 1.394            | 1.7                           | 0.31                    | 0.23                   | 17.83          | ---             | ---             | ---             | ---             |
| J154435.08+484411.1        | 2.041            | 0.917 (1.385)    | 2.4 (1.1)                     | 0.31                    | 0.24                   | 18.98          | ---             | ---             | ---             | ---             |
| J170220.06+591538.6        | 1.798            | 0.724            | 1.8                           | 0.32                    | 0.28                   | 18.73          | ---             | ---             | ---             | ---             |
| J171123.04+311613.7        | 2.041            | 1.256 (1.697)    | 2.3 (1.9)                     | 0.31                    | 0.27                   | 18.65          | ---             | ---             | ---             | ---             |

Magnitudes are corrected for Galactic extinction using the prescription of Schlegel et al. (1998). Photometric errors for the SDSS $i$-band photometry are normally $<0.03$ mag and for the UKIDSS photometry $\approx 0.05$ mag. The absorber redshifts and EWs in brackets correspond to those spectra which have two Mg II systems with EW $>1$ Å. Errors in the rest-frame EWs are typically $\pm 0.1$ Å. $E(B - V)_{\text{Fitz}}$ is the result of the fit to the extinction curve of Fitzpatrick (1999) with $R_V = 2.1$ (see Appendix A). Systems that have been the subject of previous investigations are designated $(^a)$ Srianand et al. (2008), $(^b)$ Wild & Hewett (2005a), $(^c)$ Zhou et al. (2010), $(^d)$ Wild et al. (2006) and $(^e)$ Jiang et al. (2010).

Figure 17. Left-hand panel: The EW distribution of the absorber sample (solid-line), and corresponding dust-corrected EW distribution (dashed-line), which has been calculated using equation 6. Right-hand panel: The redshift distribution of the absorber base sample (solid-line), and the corresponding dust-corrected distribution (dashed-line).
### Dusty Mg II Absorbers

Vening absorbers, dictates whether an object is observed and absorption systems identified. Therefore, one would expect a larger number of moderate $E(B-V)$ absorption systems to be present in GRB spectra than quasar spectra.

Prochter et al. (2006) identified 14 strong intervening Mg II systems (at a mean redshift of $z = 1.1$) along 14 GRB sight lines, an incidence roughly four times higher than along sight lines to quasars. The result is not expected if both GRBs and quasars sample random lines of sight. Since the intervening absorption systems are thought to be independent of the background source, the observed discrepancy has led to a call to review the fundamental assumptions that underpin extragalactic absorption line research. The discrepancy was confirmed by Sudilovsky et al. (2007), but the amplitude has since been reduced to a factor of 2.1 ± 0.6 using a larger sample of 22 absorbers (Vergani et al. 2009).

A series of explanations have been suggested to explain the observed GRB/quasar discrepancy. Porciani et al. (2007) claim that strong Mg II absorbing gas may be intrinsic to the GRB circumburst environment or originate from supernova remnants lying in the same star-forming region. It is also claimed (Prochter et al. 2006; Porciani et al. 2007; Tejos et al. 2009) that source amplification due to strong gravitational lensing may bias the GRB spectral samples toward targets that contain more intervening absorbers. Another mechanism has been proposed (Frank et al. 2007), which claims that the discrepancy is due to the different beam sizes of GRBs and quasars, but this has subsequently been ruled out by observational analysis (Pontzen et al. 2007). Finally, a number of authors (Prochter et al. 2006; Porciani et al. 2007) have suggested that dust associated with strong Mg II systems results in a reduction in the observed number of absorbers seen along sight lines to quasars in flux-limited catalogues. In general, most authors agree that the differences between Mg II toward quasar and GRB sight lines cannot be due to a single effect, but dusty absorbers have not been thought to be a significant factor.

In light of our findings on the existence of a significant population of dusty Mg II absorbers, we can provide a more definitive determination of the effect of dust on the GRB/quasar sight line discrepancy. Using a sample of GRB sight lines with intervening absorbers we can assess how this sample would suffer from incompleteness if the sight lines were instead illuminated by quasars. We assume that the GRB sample is unbiased and probes all intervening Mg II absorbers up to a moderate absorber $E(B-V)$ of 0.2 mag. Given an EW and redshift distribution of Mg II absorbers in GRBs similar to our quasar sample (Fig. 17), we would expect the GRB sight lines to show the missing 24 per cent of absorbers (Section 5.4). However, in general GRB spectra contain absorbers with different redshift and EW distribution to the absorbers in quasar spectra. The observed discrepancy in number density due to dust will be sensitive to such differences.

Two GRB absorber samples in the literature are the Vergani et al. (2009) sample and the Fynbo et al. (2009) sample. The Vergani et al. sample contains 22 strong systems (EW > 1 Å) identified using high-resolution UVES sample and a series of high- and low-resolution GRB afterglow spectra from the literature. The Fynbo et al. sample contains 15 strong systems present in the follow-up spectra of 77 optical afterglows of Swift detected GRBs. The redshift distributions of the two samples are shown in Fig. 18-(left).

The redshift distributions for the two GRB samples both exhibit a larger fraction of absorbers at high redshift compared with the quasar absorber redshift distribution. Fig. 18-(right) shows the degree to which both samples suffer from EW incompleteness by comparing the EW distributions with an exponential (Nestor et al. 2005) of the form

$$N(W_0^{\lambda_{2796}}) \propto e^{-W_0^{\lambda_{2796}}/W^*}$$

(11)

where $W^*$ is the exponential scale factor. A fit to the corrected quasar absorber EW distribution (Fig. 17) gives a value of $W^* = 0.746 ± 0.008$. Scaling the corrected quasar EW distribution using the redshift paths appropriate to the two GRB-derived samples results in the predicted number versus EW distributions for the Vergani et al. and Fynbo et al. GRB samples shown in Fig. 18-(right). Both samples are expected to be incomplete at low EW but the scaled distribution functions accurately describe the Vergani et al. sample with EW $\geq$ 2.0 Å, and the Fynbo et al. sample is consistent over the interval $\geq$ 2.0–5.0 Å. Our flux-limited quasar-derived Mg II absorber distribution has no information regarding high-EW systems with $W_0^{\lambda_{2796}} >$ 5.0 Å (where the associated large $E(B-V)$ essentially removes nearly all such systems from the SDSS quasar sample). The extension of the distribution of Mg II absorbers beyond $W_0^{\lambda_{2796}} >$ 5.0 out to $\approx$ 10 Å is clear and strongly suggests that the absorber dust-induced differences between quasar-derived and GRB-derived samples will be even larger than calculated using our $N(W_0^{\lambda_{2796}})$ parametrization.

We can calculate the fraction of absorbers that would be missed in corresponding flux-limited quasar sample by estimating an $E(B-V)$ according to equation 7 and assigning a weighting according to the dust obscuration bias/signal-to-noise ratio effects (equation 6). The predicted discrepancy is obtained by calculating the fraction of absorbers that are missed from a quasar-derived sample with an $W_0^{\lambda_{2796}}$ distribution corresponding to Equation 11 (with $W^* = 0.746$) and redshift distributions of the Vergani et al. and Fynbo et al. (2009) absorbers.

The strong dependence of the dust content on the EW of the Mg II absorbers means that the degree to which the incidence of absorbers is affected is a very strong function of the low EW limit of the samples (where the majority of absorbers reside). Fig. 19 shows the predicted discrepancies for a sample with the same absorber redshift distributions as Vergani et al. (2009) and Fynbo et al. (2009) as a function of the lower EW limit for the absorber sample. The increasing impact of dust, as samples with increasingly large lower EW limits are considered, illustrates the importance of incorporating quantitative estimates when inter-comparing results from different observed samples. The discrepancy reaches a full factor of two for $W_0^{\lambda_{2796}} >$ 2.4 Å.

Our results are consistent with the investigation of Tejos et al. who find no significant increase in number density of low-EW absorbers, EW $< 1$ Å, towards GRBs. For GRB samples where high-EW absorbers (EW $> 2$ Å) represent a

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16 Note that the procedure adopted is inherently conservative because the parametrized dependence of the $E(B-V)$ values on $W_0^{\lambda_{2796}}$ reduces the impact of individual dusty absorbers.

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significant fraction of the absorber sample, our predicted enhancement in Mg II number density is a factor two compared to absorber samples seen towards SDSS-selected quasars. The evidence from the Fynbo et al. sample for the existence of a significant number of absorbers with $W_0^\lambda > 2796\,\AA$ as high as 10 $\sigma$ suggests that the true discrepancy will be significantly greater than shown in Fig. 19 for samples with minimum detectable $W_0^\lambda > 2796\,\AA$ above 1 $\AA$. The amplitude of the enhancement is higher than has been reported in the literature hitherto and dusty absorbers could be responsible for a significant proportion of the absorber number density enhancement seen towards GRBs.

A careful study of the incidence of Mg II absorbers towards a third class of objects, the BL Lacs (or Blazars), whose selection is closely akin to GRBs in not being flux-limited in the optical, has been conducted by Bergeron et al. (2011). They find an excess of Mg II absorbers along Blazar sight lines compared with quasar sightlines of $\sim 2.0$ with no apparent difference between low-EW absorbers (EW $< 1\,\AA$), and high-EW absorbers (EW $> 1\,\AA$). However, the absorber sample is numerically small and while strong differences between low- and high-EW absorbers are not present, less significant differential effects as a function of absorber EW are not ruled out with any confidence.

Our estimate of the true number density of strong (EW $> 1\,\AA$) Mg II absorbers along sight lines to SDSS quasars is some 15 per cent higher than the value used by Bergeron et al. (2011), reducing the observed overdensity somewhat. The median redshift of the Blazar absorber sample is low, even lower than for the SDSS quasars sample presented here ($\bar{z} = 0.84$ compared to $\bar{z} = 1.1$), and the effect of dusty absorbers on the statistics is correspondingly much lower than for the GRB absorber samples discussed above. Our model predicts an increased overdensity for the Bergeron et al. (2011) sample of only 15 per cent. We also note that the contribution to the overdensity signal may be redshift dependent (fig. 2 of Bergeron et al.) with the modest path-density at $z > 1.0$ producing much of the effect. The Bergeron et al. (2011) study does not offer direct support in favour of the predictions from our dusty absorber model but nor does it rule out such a contribution. However, assuming that the factor of two overdensity of absorbers at low redshifts for Blazar samples is confirmed, then more contributors, in addition to the effects of dusty absorbers, are required to explain the observed absorber overdensity towards GRBs.

6 DISCUSSION AND CONCLUSIONS

With the aid of the enormous statistical power of the SDSS, we have been able to provide an improved characterisation of the dust content of Mg II absorption systems and its effects on the properties of absorber samples obtained using magnitude-limited quasar surveys. The principal conclusions of our investigations are:

(i) We find that dust content ($E(B-V)$) in a large sample of $\sim 8300$ strong Mg II absorbers increases much more strongly as a function of absorber rest-frame equivalent width (EW) (see equation 7) than previously reported.

(ii) The effects of dust on the observed Mg II absorber population results in significant changes to the statistics of the intrinsic absorber population. We find $24 \pm 4$ per cent of absorbers are missing from the sample for EW $> 1.0\,\AA$ and $34 \pm 2$ per cent for EW $> 2.0\,\AA$. For absorbers with EW $> 3.0\,\AA$ the fraction rises to more than a factor of two.

(iii) We find no significant detection of an evolution in absorber dust content over the redshift interval $0.4 \leq z \leq 2.2$ but the constraint is relatively weak, with a 1$\sigma$ uncertainty of 0.3 in the power-law index $\alpha$ of $E(B-V) \propto (1+z)^\alpha$.

(iv) The form of the extinction curve for absorbers is found to be of SMC-type at low values of $E(B-V)$. For absorbers with modest $E(B-V) \leq 0.2$ at redshifts $z_{abs} > 1$, where the 2175 $\AA$ feature is visible in the SDSS spectra, approximately a third of the population shows evidence for the presence of dust with an LMC-like extinction curve.

(v) For absorbers with the highest $E(B-V) \gtrsim 0.3$ there is evidence for an extinction curve that differs from the SMC, LMC and MW extinction curves. The high $E(B-V)$ systems possess a 2175 $\AA$ feature similar in strength to that seen in the MW but the overall shape of the extinction curve in the near-ultraviolet through to the near-infrared, is greyer than any of the SMC, LMC or MW extinction curves.

(vi) The impact of dust on the observed discrepancy in the Mg II absorber sight line densities between GRBs and quasars depends on both the absorber redshift distribution and the minimum equivalent width limit of the samples obtained towards GRBs. Samples with high lower EW-limits for the detection of Mg II absorbers and significant redshift path for absorbers at high redshifts are most affected. Published GRB samples are predicted to possess absorber densities a full factor of two greater than for quasars from flux-limited samples due to the effects of dust extinction.

Higher EW Mg II systems are found to exhibit a higher star formation rate (Ménard et al. 2009) and the dependence...
of $E(B - V)$ on EW can be explained in terms of the star formation rate of the absorbing galaxy. Supernovae associated with star formation impart mechanical energy to the cold MgII absorbing gas, which leads to velocity spreading of the absorption feature and a consequent increase in the observed absorber EW. An increased amount of star formation also leads to increased dust production. The presence of a larger amount of dust in absorbers associated with the highest star formation rate has potential consequences for determining the redshift-evolution of absorbers with the highest EWs although the impact on the overall star formation rate density of the Universe (Hopkins 2004) is unlikely to be more than a perturbation.

Explaining the observed differences between the MgII absorber density towards quasars in flux-limited samples, GRBs and BL Lacs requires considerably larger absorber samples to map out the dependence of the differences on absorber EW and redshift. While the explanation will almost certainly involve more than one effect, the results presented here show that obscuration due to dust associated with the absorbers is almost certainly a significant factor.

To date, the limited statistics available has meant that constraints on the dust content and form of the extinction curves associated with metal absorbers have been weak. The availability of metal absorber samples with $\sim$10 000 systems and the detection of a small number of systems with $E(B - V) \gtrsim 0.3$ is changing the situation, as shown in this paper. At low values, $E(B - V) \lesssim 0.05$, the extinction curve appears to be essentially featureless in the near-ultraviolet with an SMC-like form. A new result from our study is the detection of a weak 2175 Å feature in a significant fraction of MgII absorbers with $E(B - V) \approx 0.1-0.2$, consistent with an LMC-like extinction curve. Individual systems with higher $E(B - V)$ values of $\gtrsim 0.3$ and an apparent strong 2175 Å feature have been identified in recent years. Our results for the MgII absorbers with the highest $E(B - V)$ values, particularly the small subset with near-infrared photometry available, indicate that there may be a systematic dependence in the form of the extinction curve as a function of $E(B - V)$ and, more fundamentally, the column density of the absorbers. Obtaining near-infrared photometry, to combine with SDSS spectra, for a larger sample of such objects is necessary to establish the general nature of any such trend. Confirmation of a systematic change in the form of the extinction curve as advocated here, from featureless and SMC-like at low $E(B - V)$, through to greyer overall than any of the SMC, LMC or MW curves but with a strong 2175 Å feature (consistent with the low $R_V$ form presented by Fitzpatrick (1999)) at high $E(B - V)$, would provide powerful constraints on models of star formation and chemical enrichment histories for physical systems associated with metal absorbers over an extended range in column density.

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APPENDIX A: EXTINCTION CURVES
Figure A1. The Fitzpatrick (1999) extinction curve with $R_V = 2.1$.

Table A1. The Fitzpatrick (1999) extinction curve with $R_V = 2.1$, over the wavelength range 1000 - 25000 Å.

| $\lambda$ / Å | $E(\lambda - V)/E(B - V)$ | $\lambda$ / Å | $E(\lambda - V)/E(B - V)$ |
|---------------|----------------------------|---------------|----------------------------|
| 1000          | 17.338                     | 4000          | 1.316                      |
| 1050          | 15.362                     | 4500          | 0.863                      |
| 1100          | 13.754                     | 5000          | 0.379                      |
| 1150          | 12.434                     | 5500          | -0.071                     |
| 1200          | 11.341                     | 6000          | -0.416                     |
| 1250          | 10.429                     | 6500          | -0.663                     |
| 1300          | 9.664                      | 7000          | -0.844                     |
| 1350          | 9.018                      | 7500          | -0.982                     |
| 1400          | 8.472                      | 8000          | -1.090                     |
| 1450          | 8.010                      | 8500          | -1.177                     |
| 1500          | 7.619                      | 9000          | -1.249                     |
| 1550          | 7.292                      | 9500          | -1.310                     |
| 1600          | 7.021                      | 10000         | -1.364                     |
| 1650          | 6.803                      | 10500         | -1.411                     |
| 1700          | 6.638                      | 11000         | -1.453                     |
| 1750          | 6.520                      | 11500         | -1.490                     |
| 1800          | 6.451                      | 12000         | -1.525                     |
| 1850          | 6.443                      | 12500         | -1.557                     |
| 1900          | 6.509                      | 13000         | -1.587                     |
| 1950          | 6.663                      | 13500         | -1.614                     |
| 2000          | 6.907                      | 14000         | -1.639                     |
| 2050          | 7.214                      | 14500         | -1.662                     |
| 2100          | 7.499                      | 15000         | -1.684                     |
| 2150          | 7.624                      | 15500         | -1.704                     |
| 2200          | 7.479                      | 16000         | -1.722                     |
| 2250          | 7.079                      | 16500         | -1.739                     |
| 2300          | 6.540                      | 17000         | -1.755                     |
| 2350          | 5.984                      | 17500         | -1.770                     |
| 2400          | 5.478                      | 18000         | -1.784                     |
| 2450          | 5.043                      | 18500         | -1.797                     |
| 2500          | 4.675                      | 19000         | -1.809                     |
| 2550          | 4.364                      | 19500         | -1.820                     |
| 2600          | 4.099                      | 20000         | -1.830                     |
| 2650          | 3.870                      | 20500         | -1.840                     |
| 2700          | 3.670                      | 21000         | -1.849                     |
| 2750          | 3.480                      | 21500         | -1.858                     |
| 2800          | 3.307                      | 22000         | -1.866                     |
| 2850          | 3.148                      | 22500         | -1.873                     |
| 2900          | 3.002                      | 23000         | -1.881                     |
| 2950          | 2.868                      | 23500         | -1.887                     |
| 3000          | 2.744                      | 24000         | -1.894                     |
| 3500          | 1.868                      | 24500         | -1.900                     |