On the H I content, dust-to-gas ratio and nature of Mg II absorbers

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ABSTRACT

We estimate the mean dust-to-gas ratio of Mg II absorbers as a function of rest equivalent width $W_0$ and redshift over the range $0.5 < z < 1.4$. Using the expanded Sloan Digital Sky Survey/Hubble Space Telescope sample of low-redshift Lyman-α absorbers, we first show the existence of a $8\sigma$ correlation between the mean hydrogen column density $\langle N_{\text{H}} \rangle$ and $W_0$, an indicator of gas velocity dispersion. By combining these results with recent dust-reddening measurements, we show that the mean dust-to-gas ratio of Mg II absorbers does not appreciably depend on rest equivalent width. Assuming that, on average, dust-to-gas ratio is proportional to metallicity, we find its redshift evolution to be consistent with that of $L^*$ galaxies from $z = 0.5$ to $1.4$, and we show that our constraints disfavour dwarf galaxies as the origin of such absorbers. We discuss other scenarios and favour galactic outflows from $\sim L^*$ galaxies as the origin of the majority of strong Mg II absorbers. Finally, we show that, once evolutionary effects are taken into account, the Bohlin et al. relation between $A_V$ and $N_{\text{H}}$ is also satisfied by strong Mg II systems down to lower column densities than those probed in our Galaxy.

Key words: ISM: dust, extinction – galaxies: haloes – quasars: absorption lines.

1 INTRODUCTION

A successful theory of galaxy formation must not only explain the properties of the luminous parts of galaxies but it is equally important to account for the material seen in absorption against background sources. However, while the connection between strong absorbers and galaxies was realized a long time ago (Bahcall & Spitzer 1969; Bergeron 1986), our physical understanding of absorption-selected systems has not yet reached the maturity of current models addressing the emission properties of galaxies. In particular, the nature of the structures probed by some of the strongest absorption features is not yet understood (e.g. Wolfe, Gawiser & Prochaska 2005).

Exploring the existence of scaling relations for absorbers may provide us with useful insight to constrain the physical conditions and establish theoretical models for these systems and their associated galaxies. In this paper, we investigate the properties of the dust-to-gas ratio of Mg II absorbers, i.e. the strongest metal line detectable in optical spectra at $z \lesssim 2$ and in some cases a tracer of damped Lyman-α absorbers (DLAs) (e.g. Churchill, Kacprzak & Steidel 2005). We first present new correlations involving gas velocity dispersion, hydrogen and dust column densities, and show how the knowledge of the dust-to-gas ratio sheds light on the nature of strong Mg II absorber systems.

The dust-to-gas ratio is one of the basic properties of the interstellar and intergalactic media but our knowledge of this quantity is largely based on our own Galaxy, some of its satellites and a few objects with $z > 0$ using for example multiple images in strongly lensed systems (Zuo et al. 1997; Dai & Kochanek 2008) or absorbers in front of gamma ray bursts (Ellison et al. 2006). Interestingly, the Milky Way presents a characteristic value of the extinction per H atom. Using hydrogen Lyman-α and H₂ absorption lines to determine the total H column densities along star sight lines, Bohlin, Savage & Drake (1978) found that the extinction in the V band follows

$$A_V \simeq 0.53 \left( \frac{N_{\text{H}}}{10^{21} \text{cm}^{-2}} \right) \text{mag} \quad \text{for} \quad R_V = 3.1, \quad (1)$$

with a scatter about the mean of about 30 per cent and where $R_V = A_V/E(B - V)$. This relation was initially observed over the range of column densities $10^{20} \lesssim N_{\text{H}} \lesssim 3 \times 10^{22} \text{ cm}^{-2}$ and then extended and confirmed up to $N_{\text{H}} \sim 5 \times 10^{22} \text{ cm}^{-2}$, where molecular hydrogen plays an important role (Snow, Rachford & Figoski 2002). The linearity and slope of the above relation carry information on the complex mechanisms responsible for the formation and destruction of dust grains. It is interesting to investigate whether such a relation holds at lower column densities (where ionization corrections could be important) and/or in different environments, such as larger galactic radii and higher redshifts.

By extrapolating the above relation, column densities with $N_{\text{H}} \lesssim 10^{20} \text{ cm}^{-2}$ are expected to be associated with $E(B - V)$ values smaller than a few $\times 10^{-2}$ mag. Measuring such an effect along individual star sight lines becomes challenging and a statistical approach is required. Such a technique was recently used with DLAs by Vladilo, Prochaska & Wolfe (2008) and Mg II...
absorbers by York et al. (2006), Wild, Hewett & Pettini (2006) and Ménard et al. (2008). In particular, the latter authors constrained the reddening induced by Mg II absorbers down to $E(B - V) \sim 5 \times 10^{-3}$ mag by analysing $\sim$7000 intervening systems.

By combining the reddening constraints of Mg II absorbers with measurements of hydrogen column densities, the present analysis will allow us to obtain constraints on the dust properties in new regimes, i.e. at $z \sim 1$ and on large scales ($\sim$50 kpc) around galaxies. In particular, we will show that the inferred dust-to-gas ratio of Mg II is similar to that given by the Bohlin et al. (1978) relation extrapolated down to lower hydrogen column densities.

Throughout this paper, we will simply refer the dust-to-neutral gas ratio as the dust-to-gas ratio unless stated otherwise. The amount of dust will be quantified by either $E(B - V)$ or $A_V$. The Mg II rest equivalent width, $W_0$, denotes the 2796 Å transition.

2 THE DATA

The data used in this analysis come from two sources: (i) ‘the expanded Sloan Digital Sky Survey (SDSS)/Hubble Space Telescope (HST) sample of low-redshift Lyman-α absorbers’ compiled by Rao, Turnshek & Nestor (2006) and (ii) the characterization of the reddening effects induced by Mg II absorbers in the SDSS by Ménard et al. (2008). We briefly describe them below.

The expanded SDSS/HST sample of low-redshift Lyman-α absorbers consists of 197 systems and represents the largest sample of ultraviolet (UV)-detected DLAs ever assembled. It has been compiled from UV spectra of quasi-stellar objects with Mg II systems optically identified in the range $0.11 < z < 1.65$. The Mg II absorber systems were selected from various sources in the literature (see Rao et al. 2006 for references). Most of the UV data were obtained with observing programmes on HST led by Rao as well as archival data.

In Fig. 1, we show the distribution of neutral hydrogen column density, $N_{\text{HI}}$, as a function of $W_0$ rest equivalent width, with $0.45 < W_0 < 3.3$ Å. The arrows show upper limits on $N_{\text{HI}}$. They represent about 3 per cent of the data points and can safely be neglected in the present analysis. An important point to emphasize is the large scatter in $N_{\text{HI}}$ (up to 3 orders of magnitude) even at a fixed value of $W_0$. The colour coding of the points refers to the measured rest equivalent width of Fe II at 2600 Å. Empty circles are used for upper limits.

The second set of observational results used in our analysis comes from the recent dust-reddening analysis done by Ménard et al. (2008). Using almost 7000 Mg II absorbers detected in SDSS quasar spectra, these authors have measured the mean colour excess $E(B - V)$ induced by these systems as a function of the rest equivalent width and the redshift. Such constraints will be used to compute the dust-to-gas ratio of Mg II absorbers.

It is useful to recall that the majority of Mg II absorption lines with $W_0 \geq 1$ Å are saturated (Nestor, Turnshek & Rao 2005) and that, therefore, the rest equivalent width of the lines provides us with an estimate of the gas velocity dispersion. For a completely saturated line, 1 Å corresponds to $\Delta v \simeq 107$ km s$^{-1}$. Using high-resolution spectroscopy, the absorption is often seen to originate from several velocity components implying that this value is only a lower limit on the total velocity dispersion of the system. Empirically, it has been observed that $\Delta v \simeq 120$ km s$^{-1}$ Å$^{-1}$ (Ellison 2006, fig. 3). This value will be used below for physical interpretations.

3 THE DISTRIBUTION OF HYDROGEN COLUMN DENSITIES

The expanded SDSS/HST sample of low-redshift Lyman-α absorbers was used by Rao et al. (2006) to quantify the amount of neutral hydrogen probed by Mg II absorbers at $z < 1.65$ and to estimate the mean hydrogen density $\langle N_{\text{HI}} \rangle$. To do so, these authors computed the mean H I column density as a function of $W_0$(Mg II):

$$\langle N_{\text{HI}} \rangle(W_0) = \frac{1}{N} \sum_{i=1}^{N} N_{\text{HI},i},$$

and found $\langle N_{\text{HI}} \rangle \sim 10^{21}$ cm$^{-2}$ for the range of $W_0 > 0.6$ Å. In Fig. 1, we show the arithmetic mean of $N_{\text{HI}}$ in green, using a logarithmic binning in $W_0$. We have used 500 bootstrap samples in order to estimate the errors on the mean in each bin. We recover the lack of correlation between mean hydrogen column density reported by Rao et al. (2006). For $W_0 > 0.6$ Å, we find $\langle N_{\text{HI}} \rangle \simeq 3 \times 10^{20}$ cm$^{-2}$.

While the use of the arithmetic mean is needed to quantify the amount of neutral hydrogen probed by Mg II absorbers, which is important to constrain the evolution of H I through cosmic time, it ends up being sensitive to a small fraction of the data points, having the largest $N_{\text{HI}}$ values. Indeed, the distribution $P(N_{\text{HI}}|W_0)$
is highly asymmetric and spans about 3 orders of magnitude in the present data set. The value of \( N_{\text{HI}} \) is therefore driven by a small fraction of the data points. Even if it is computed from a sample of \( \sim 200 \) objects, it might effectively suffer from small-number statistics.\(^1\)

More importantly the arithmetic mean of \( N_{\text{HI}} \) does not provide relevant information regarding the majority of \( \text{Mg}\,\text{II} \) absorbers and is therefore not suited to extract underlying correlations between the parameters \( N_{\text{HI}} \) and \( W_0 \). However, additional information can be extracted, and we first consider the geometric mean of \( N_{\text{HI}} \):

\[
\langle N_{\text{HI}} \rangle_g (W_0) = 10^{\log N_{\text{HI}}}. \tag{3}
\]

We compute it using the same binning in \( W_0 \), and the errors are again estimated with bootstrap resampling. The results are shown in Fig. 1 with the red data points. We can now detect a strong correlation between the hydrogen column density \( N_{\text{HI}} \) and the \( \text{Mg}\,\text{II} \) rest equivalent width \( W_0 \), and a simple power-law fit gives

\[
\langle N_{\text{HI}} \rangle_g (W_0) = C_g (W_0)^{p_g} \tag{4}
\]

where the subscript ‘\( g \)’ denotes a geometric mean, \( C_g = (3.06 \pm 0.55) \times 10^{19} \text{ cm}^{-2} \) and \( \alpha_g = 1.73 \pm 0.26 \). This correlation holds over 1 order of magnitude in \( W_0 \). Its significance, quantified by that of the slope, is greater than 6\( \sigma \).

To demonstrate the robustness of the above result, we repeat the procedure and estimate the median of \( N_{\text{HI}} \) as a function of \( W_0 \). The results are shown in Fig. 1 with orange points. They show consistency with the results obtained using the geometric mean. Similarly, a power-law fit gives

\[
\text{med} \left[ N_{\text{HI}} \right] (W_0) = C_m (W_0)^{p_m} \tag{5}
\]

with \( C_m = (2.45 \pm 0.38) \times 10^{19} \text{ cm}^{-2} \) and \( \alpha_m = 2.08 \pm 0.24 \). The correlation is now detected at 8.7\( \sigma \). Consistent fitting parameters are obtained using both estimators which show that, even if there is a large scatter between \( N_{\text{HI}} \) and \( W_0 \), there exists an underlying and well-defined correlation between them. Both the geometric mean and the median allow us to measure a signal coming from the majority of the systems, and not from a few outliers. It is interesting to mention that the correlation weakens as we increase the lower limit of \( N_{\text{HI}} \), but it is not severely affected if we decrease the higher limit of \( N_{\text{HI}} \) (the opposite statement would apply to the arithmetic mean.).

Our results indicate that, typically, \( N_{\text{HI}} \) is roughly proportional to the square of \( W_0 \).

Similarly, we can quantify the relations between \( N_{\text{HI}} \) and \( \text{Fe}\,\text{II} \) rest equivalent width. By doing so we should keep in mind that the sample used in this analysis is \( \text{Mg}\,\text{II} \)-selected. The corresponding \( \text{Fe}\,\text{II} \)-related correlations are valid in this context only.

We have applied the three estimators introduced previously and summarized the results in Table 2. The correlation between the two parameters is detected at a high significance (8\( \sigma \) and 12\( \sigma \)) and is closer to a simple proportionality.\(^2\) Such a behaviour is expected as the 2600 Å \( \text{Fe}\,\text{II} \) absorption line has a lower oscillator strength than the \( \text{Mg}\,\text{II} \) doublet. It is therefore less subject to saturation and carries more information about the column density of the absorbing system.

### 4 Dust-to-gas ratio

The presence of dust associated with \( \text{Mg}\,\text{II} \) absorbers has been reported by several authors (Ménard & Péroux 2003; Wang et al. 2004; Khare et al. 2005; York et al. 2006; Wild et al. 2006). Recently, Ménard et al. (2008) analysed close to 7000 strong \( \text{Mg}\,\text{II} \) absorbers and quantified the amount of reddening as a function of rest equivalent width and redshift. In particular, they find a scaling relation between the amount of reddening and the \( \text{Mg}\,\text{II} \) rest equivalent width:

\[
\langle E(B - V)_{\text{red}} \rangle (W_0, z) = C \times \left( \frac{W_0}{1 \text{ Å}} \right)^{\alpha} (1 + z)^{\beta}, \tag{6}
\]

where \( \alpha = 1.88 \pm 0.17, \beta = -1.1 \pm 0.4 \) and \( C = (0.60 \pm 0.07) \times 10^{-2} \text{ mag} \). This relation has been constrained over the range \( 1 < W_0 < 6 \text{ Å} \). The similarity of equations (6) and (4) is striking and suggests that the average dust-to-gas ratio of \( \text{Mg}\,\text{II}-\)selected systems does not strongly depend on the rest equivalent width. We now quantify this statement by measuring the dust-to-gas ratio in the range of \( \text{Mg}\,\text{II} \) rest equivalent widths common to both data sets, i.e. \( 1 < W_0 < 3.3 \text{ Å} \).

To do so, we have rerun the reddening analysis by Ménard et al. (2008) selecting only \( \text{Mg}\,\text{II} \) absorbers with \( 0.4 < z < 1.4 \) so that the redshift distributions of the two data sets are similar. It is important to note that the median and arithmetic means give consistent results for the reddening analysis.\(^3\) This is probably due to the fact that the high dust column density systems cannot be detected in the SDSS due to the extinction bias and therefore the tail of the reddening distribution cannot be probed. Richards et al. (2003) and Ménard et al. (2008) showed that quasars reddened by a colour excess \( E(B - V) \) greater than about 0.3 mag can hardly be selected. Fortunately, this effect is not expected to strongly bias the reddening constraints as Ellison et al. (2004) showed, using radio-selected quasars, that not more than 20 per cent of optically selected quasars are missed due to extinction effects associated with strong \( \text{Mg}\,\text{II} \) absorbers.

#### 4.1 Dependence on \( W_0 \)

We present our measurements of the dust-to-gas ratio of \( \text{Mg}\,\text{II} \) absorbers in Fig. 2. The upper panel shows the variation of the geometric mean and median of \( N_{\text{HI}} \), as a function of \( \text{Mg}\,\text{II} \) rest equivalent width (upper axis) or \( \Delta \tau(\text{Mg}\,\text{II}) \), the gas velocity dispersion (lower axis). The lines show the fitted power laws described in Table 1. The middle panel shows the observed reddening values \( E(B - V) \) for \( \text{Mg}\,\text{II} \) absorbers selected with \( 0.4 < z < 1.4 \). The solid line is the fitting formula (equation 6) proposed by Ménard et al. (2008) and simply evaluated at the mean redshift of the sample. To present

\(^1\) The same problem affects estimates of the cosmological density of neutral gas, \( \Omega_g(z) \), as its estimation involves a similar average (Lanzetta et al. 1991):

\[
\Omega_g(z) = \frac{H_0}{c} \frac{\mu m_{\text{HI}}}{\rho_{\text{crit}}} \sum \frac{N_{\text{HI}}}{\Delta X},
\]

where \( \mu \) is the mean molecular weight of the gas, \( m_{\text{HI}} \) is the mass of the hydrogen atom, \( \rho_{\text{crit}} \) is the current critical mass density and \( \Delta X \) is the absorption distance path. This effective small-number statistic might be at the origin of the discrepancies in \( \Omega_g \) currently debated in the literature.

\(^2\) We also note that a double power law is a more accurate representation of the data in the \([N_{\text{HI}}, W_0(\text{Fe}\,\text{II})]\) plane. This is certainly an interesting feature to address but is beyond the scope of this paper, focusing on \( \text{Mg}\,\text{II} \) absorption.

\(^3\) The geometric mean cannot be computed as the signal originates from positive and negative fluctuations.
the results in convenient units, we convert $E(B - V)$ reddening values into visual extinction $A_V$ using a Small Magellanic cloud (SMC) extinction curve, i.e. $R_V = 3.1$ as motivated by York et al. (2006) and Ménard et al. (2008). We use the ratio between $A_V$ and $N(H_i)$ (directly obtained from the data) as an estimate of the mean dust-to-gas ratio of Mg ii absorbers.\footnote{Ideally, the average dust-to-gas ratio $\langle A_V/N(H_i) \rangle$ can be estimated by weighting the individual reddening measurements by $1/N(H_i)$, as done by Vladilo et al. (2008). In this study, the number of objects for which $N(H_i)$ is available is unfortunately too small to provide us with a reddening detection.} For systems with $1 < W_0 < 3.3$ Å, we find using the geometric mean or the median of $10^{19}$ values into visual extinction $A_V$ that does not significantly depend on the Mg ii gas velocity width.

### Table 1. Scaling parameters.

<table>
<thead>
<tr>
<th>$N(H_i)$ versus $W_0$(Mg ii)</th>
<th>Amplitude (atom cm$^{-2}$)</th>
<th>Power-law index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arithmetic mean</td>
<td>$(2.37 \pm 0.63) \times 10^{20}$</td>
<td>$0.32 \pm 0.35$</td>
</tr>
<tr>
<td>Geometric mean</td>
<td>$(3.06 \pm 0.55) \times 10^{19}$</td>
<td>$1.73 \pm 0.26$</td>
</tr>
<tr>
<td>Median</td>
<td>$(2.45 \pm 0.38) \times 10^{19}$</td>
<td>$2.08 \pm 0.24$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$N(H_i)$ versus $W_0$(Fe ii)</th>
<th>Amplitude (atom cm$^{-2}$)</th>
<th>Power-law index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arithmetic mean</td>
<td>$(2.49 \pm 0.44) \times 10^{20}$</td>
<td>$1.54 \pm 0.12$</td>
</tr>
<tr>
<td>Geometric mean</td>
<td>$(7.85 \pm 1.14) \times 10^{19}$</td>
<td>$1.34 \pm 0.11$</td>
</tr>
<tr>
<td>Median</td>
<td>$(5.74 \pm 1.33) \times 10^{19}$</td>
<td>$1.46 \pm 0.18$</td>
</tr>
</tbody>
</table>

\[ \langle A_V \rangle = 3.0 \pm 0.6 \times 10^{-22} \text{mag cm}^2 \]

at a mean redshift close to unity. This value is less than a factor of 2 lower than that of the Milky Way. It is interesting to note that while the shape of the mean extinction curve of Mg ii absorbers is consistent with that of the SMC, i.e. does not present the 0.2 μm bump (York et al. 2006; Ménard et al. 2008), the mean dust-to-gas ratio is substantially higher than that of the SMC.

Interestingly, the mean dust-to-gas ratio does not appear to be a strong function of $W_0$. While both the mean hydrogen and dust column densities vary by more than an order of magnitude over this range, the mean dust-to-gas ratio is consistent with being constant and is found to vary by less than a factor of ~2 in this interval for the current sample. In comparison, the dust-to-gas ratios of the Milky Way and the SMC differ by a factor of ~8.5. A power-law fit to the observed dust-to-gas ratio as a function of Mg ii rest equivalent width gives

\[ \langle A_V \rangle \propto (W_0)^{\gamma_V} \quad \{ \gamma_V = 0.5 \pm 0.7 \} \]

\[ \gamma_V = 0.4 \pm 0.8. \]

A large scatter in the relation between dust-to-gas ratio and Mg ii rest equivalent width may exist if we consider individual systems; however, our results show that the mean dust-to-gas ratio of Mg ii-selected systems is not a strong function of gas velocity dispersion. The lack of strong correlation is an interesting property.

If we assume that the dust-to-gas ratio is, on average, proportional to metallicity, the trend reported in equation (8) indicates that the mean metallicity of Mg ii absorbers is a weak function of rest equivalent width. The linearity between the dust-to-gas ratio and metallicity is expected as dust is formed from metals and the mass of metals is equal to the product of the metallicity and the gas mass. This linear correlation has been shown in nearby galaxies (Issa, MacLaren & Wolfendale 1990; Boissier et al. 2004) or in high redshift DLAs (Vladilo et al. 2006) over several orders of magnitude in column densities.

Given the existence of a stellar mass–metallicity relation (Tremonti et al. 2004), the apparent lack of correlation between the mean dust-to-gas ratio and the velocity dispersion of the gas implies that the mean mass of galaxies giving rise to strong Mg ii absorption does not play a dominant role in determining $W_0$. In other words, the velocity dispersion of the gas does not reflect the gravitational potential of the system. By analysing the correlation between the mean luminosity of Mg ii absorbing galaxies and $W_0$, several authors have reported similar results. Using a sample of 58 Mg ii absorber–galaxy associations, Steidel et al. (1997) did not find any correlation between the galaxy luminosity and absorber rest equivalent width. Similar results were also found by Zibetti et al. (2007) who stacked the images of ~2500 SDSS quasars with strong Mg ii absorbers and Kacprzak et al. (2007) who reported a lack of correlation between Mg ii absorption and galaxy morphology from HST data.

The present analysis allows us to probe only a factor of ~3.3 in Mg ii rest equivalent width, which corresponds to the velocity widths in the range of $\Delta v \lesssim 400$ km s$^{-1}$. The number of absorbers per unit rest equivalent width and redshift is given by Nestor et al. (2005):

\[ \partial N/\partial W_0 = N^*/W_0 e^{-W_0/W_0^*}, \]

![Figure 2](https://academic.oup.com/mnras/article-abstract/393/3/808/967399/3)
with the maximum likelihood values $W^* = 0.702 \pm 0.017 \, \AA$ and $N^* = 1.187 \pm 0.052$. The steep exponential decline implies that the incidence of systems with $W_0 \gtrsim 1 \, \AA$ is about 30 times higher than that of systems with $W_0 \simeq 3.3 \, \AA$. The sharp decrease of $dN/dW_0$ may be due to a transient nature of the absorbing gas, such as outflows triggered by star formation.

These results may, at first, appear to be in contrast with direct measurements of metallicities and Mg ii rest equivalent widths reported by Murphy et al. (2007). These authors found $\langle Z \rangle \simeq (1.69 \pm 0.20)\log(W_0) + c$ which indicates a substantially steeper dependence on $W_0$. However, their sample selection significantly differs from ours: their study is not based on Mg ii-selected absorbers in general, but focuses only on systems with both detections of hydrogen column density and a metallic absorption line from a volatile element. As a result of this additional selection criterion, the distribution of points in the $(N_{\text{HI}}, W_0)$ plane differs from the generic one compiled by Rao et al. (2006) and presented in Fig. 1. For example, at $W_0 < 1 \, \AA$, the region of the plane with $N_{\text{HI}} < 10^{21} \, \text{cm}^{-2}$ is almost unpopulated in their case, while it is where most of the points lie in the Rao et al. sample. Hence, the metallicity trend reported by Murphy et al. only applies to a specific subpopulation of Mg ii absorbers.

We postulate that, similar to the shallow dependence found between dust-to-gas ratio and $W_0$, a weak correlation is expected between metallicity and $W_0$, providing that absorbers are selected only on their Mg ii rest equivalent width. Such a measurement can be performed by using composite spectra (e.g. Nestor et al. 2003; Turnshek et al. 2005; York et al. 2006), which allows one to detect weaker absorption lines and estimate mean metallicities.

### 4.2 Redshift evolution and link to $L^*$ galaxies

Having shown that the dust-to-gas ratio of Mg ii absorbers does not strongly depend on the rest equivalent width (over the range $1 < W_0 < 3.3 \, \AA$), we now investigate its evolution as a function of redshift. Following the above procedure, we have divided both data sets into two redshift bins with $\langle z_1 \rangle \simeq 0.7$ and $\langle z_2 \rangle \simeq 1.2$ and measured the mean $A_v/N_{\text{HI}}(z)$ as defined above. We present the results in Fig. 3 and the numerical values are given in Table 2. As can be seen, the observed dust-to-gas ratio of strong Mg ii systems is, on average, similar to that of the Milky Way and significantly higher than that of the SMC, even at the highest redshift that we can probe. The data also suggest a trend of decreasing dust-to-gas ratio with increasing redshift.

As done previously, assuming that the dust-to-gas ratio is, on average, proportional to the metallicity (see Section 4.1), we can attempt to compare the observed trend to the available models. To do so, we first consider that a solar metallicity corresponds to a Milky Way dust-to-gas ratio (Bohlin et al. 1978; Issa et al. 1990):

$$\left\langle \log \left[ \frac{A_v}{N_{\text{HI}}} \right](z) \right\rangle \simeq \log \left( \frac{A_v}{N_{\text{HI}}} \right)_{\text{MW}} + \langle [Z/H] \rangle(z).$$

(10)

The above estimate strongly depends on the averaging procedure used to define the mean metallicity. Modelled evolutions of $\langle [Z/H] \rangle(z)$ have been explored by Davé & Oppenheimer (2007). These authors investigated the cosmic metal budget in various phases of baryons estimated from cosmological hydrodynamic simulations which included constrained models for enriched galactic outflows. The solid line in Fig. 3 shows their estimation of the variation of mean metallicity as a function of redshift for a star formation weighted estimator, expected to be a representative value for galaxies selected in emission. We can see that, over the entire redshift range available, the dust-to-gas ratio of Mg ii-selected systems is in agreement with the model of the metallicity evolution using a star formation weighted estimator (representative of $L^*$ galaxies) but not with the $N(\text{HI})$-weighted one (corresponding to DLAs). Even at the highest redshifts probed by our data set, the mean dust-to-gas ratio of Mg ii absorbers is significantly higher than that of the SMC at $z = 0$. For comparison, we also show the expected evolution of an $N(\text{HI})$-weighted estimator of $\langle [Z/H] \rangle(z)$ with the dashed line. As can be seen, such a trend is not in good agreement with the data points.

These results show that the mean dust-to-gas ratio of strong Mg ii absorbers is consistent with that of $L^*$ galaxies but not with that of substantially smaller systems, such as the SMC. Given that metallicity is expected to decrease with increasing redshift, an LMC-type dust-to-gas ratio is also disfavoured. It suggests that, on average, strong Mg ii systems are associated with $L^*$ galaxies (which does not prevent the existence of a large scatter around this relation if individual systems are considered).

Associations between strong Mg ii absorbers and $L^*$ galaxies have already been made observationally. As mentioned above, Steidel et al. (1997) and Zibetti et al. (2007) showed that the mean luminosity of Mg ii absorbing galaxies is about 0.8$L^*$. However, while such associations clearly gathered information on the link between strong Mg ii absorbers and $L^*$ galaxies, they have not been able to provide strong constraints on the nature of these systems. Below, we show how the knowledge of the mean dust-to-gas ratio may shed light on the origin of these systems.

<table>
<thead>
<tr>
<th>redshift</th>
<th>$A_v/N_{\text{HI}} (10^{-22} , \text{mag cm}^{-2})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z = 0.7$</td>
<td>$4.20 \pm 0.14$</td>
</tr>
<tr>
<td>$z = 1.2$</td>
<td>$3.10 \pm 0.74$</td>
</tr>
</tbody>
</table>

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**Figure 3.** The mean dust-to-gas ratio of strong Mg ii absorbers as a function of redshift. For comparison, we show an estimate of the expected dust-to-gas ratio of $\sim L^*$ galaxies from Davé & Oppenheimer (2007) as well as the values of the Milky Way, the LMC and the SMC (Gordon et al. 2003).

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4.3 Nature of the absorbing gas

The origin of Mg II absorbers has been a matter of debate since their discovery. Various scenarios have been proposed: infalling material (Mo & Miralda-Escude 1996), outflows (Bond et al. 2001),orbiting dwarf galaxies (York et al. 1986), etc. Certain studies have proposed a relation between strong Mg II absorbers and star formation: from the observed redshift distribution of $dN/dz$ (e.g. Guillemin & Bergeron 1997; Prochter, Prochaska & Burles 2006) or from the existence of a correlation between Mg II rest equivalent width and star formation rates estimated from broad-band colours Zibetti et al. (2007). While some indication of the outflow phenomenon exists in certain cases, two different origins remain: outflows can equally well originate from the bright galaxy usually found at $\sim 50–100$ kpc from the absorber or from the satellite galaxies orbiting the parent dark matter halo of the system, usually too faint to be observed and/or too close to the background quasar.

Interestingly, our result allows us to strengthen the outflow hypothesis. Considering that (i) the mean impact parameter of Mg II absorbers is about 50 kpc from a $L \sim L^*$ galaxy (Zibetti et al. 2007) and (ii) the mean dust-to-gas ratio of these systems is consistent with that of $L^*$ as a function of redshift, these suggest that the gas is originating from the neighbouring $\sim L^*$ galaxy itself. In such a context, outflows appear to be the simplest explanation to simultaneously explain these two constraints. Dwarf galaxies alone do not satisfy the second property. Our result therefore indicates that the bulk of Mg II absorbers with $W_0 > 1$ Å and $0.5 \lesssim z \lesssim 1.5$ may trace outflowing gas from galaxies. Another scenario would involve low-metallicity gas outflowing or being stripped from dwarf galaxies and experiencing a higher dust-to-neutral gas ratio due to ionization effects. Such a model is however less attractive as it requires ionization effects to coincidentally increase the dust-to-neutral gas ratio to the value of that of a $L^*$ galaxy.

In some cases, observations of individual galaxies have already pointed out to a link between strong Mg II absorbers and outflows: 500 km s$^{-1}$-blueshifted Mg II absorption has been observed in the spectra of 10 out of 14 massive post-starburst galaxies (Tremonti, Moustakas & Diamond-Stanic 2007). Recently, using integral-field spectroscopy, Bouché et al. (2007) probed H– emission within 30 kpc of Mg II absorbers with $W_0 > 2$ Å at $z \approx 0.9$, and found a 2$\sigma$ indication of correlation between Mg II rest equivalent width and H– flux based on 14 systems. Using high-resolution spectroscopy of a few strong Mg II systems, Bond et al. (2001) showed that the shape of certain absorption lines is consistent with those expected from galactic winds (but it could also be due to merging galaxies). While the above analyses dealt with individual systems, the statistical results presented in our analysis suggest that the gas traced by Mg II absorption, with a significant range of Mg II rest equivalent widths and over a substantial fraction of cosmic time, may often be associated with an outflow phenomenon.

4.3.1 The diversity of Mg II-selected systems

Mg II absorption arises in gas spanning several decades of neutral hydrogen column density and probes a wide range of environments. Locally, Mg II absorbers are known to trace diverse structures, such as the disc of our Galaxy (Bowen, Blades & Pettini 1996), in high-velocity clouds (Bowen, Blades & Pettini 1995; Savage et al. 2000) or the Large Magellanic Cloud (LMC) (Welty et al. 1999).

The use of the geometric mean or median hydrogen column density and dust-to-gas ratio has allowed us to estimate number-count-weighted quantities rather than $N_{HI}$-weighted of a Mg II-selected population. Our results aim at representing ‘typical’ systems but cannot be extended to all the objects. The distribution of $N_{HI}$ as a function of $W_0$ seems to indicate the existence of two different populations of objects: most of the points lie around the dashed lines obtained using the geometric mean or median estimates of $N_{HI}$, however others depart by 2 to 3 orders of magnitude in $N_{HI}$ from these relations and reach the DLA regime. Such systems are likely to have a different nature. First, we can observe that the absorbers with the largest hydrogen column density do not display the strongest Fe II rest equivalent width (which better correlates with metal column density than Mg II). Furthermore, their implied dust-to-gas ratio is necessarily low otherwise the background quasar would be heavily extincted. We thus postulate that these systems correspond, on average, to objects substantially less metal-rich such as dwarf galaxies. This statement is in line with the mean dust-to-gas ratio and metallicity estimates of DLAs by Vladilo et al. (2008). Using about 250 DLAs with $2.2 < z < 3.5$ detected in SDSS quasar spectra, these authors found $\langle A_V/N[H II] \rangle \approx 7 \times 10^{-22}$ mag cm$^2$, i.e. a dust-to-gas ratio order of magnitude lower than the mean values of Mg II absorbers at $z \sim 1$. As metallicity evolution is not expected to be as large between redshifts 1 and 2 (see Davé & Oppenheimer 2007 or the models summarized in Péroux et al. 2006), it indicates that the data points lying in the upper part of Fig. 1 have an average dust-to-gas ratio significantly lower than those following the median track and are likely to trace dwarf-like galaxies. As such, the absorbers deviating from the median track and populating the upper part of Fig. 1 should correspond to lines of sight intercepting galaxies less metal-rich and probably less luminous than $L^*$. It will be of interest to test this prediction with available or upcoming data sets. A similar conclusion was reached by Khare et al. (2007) based on the implied relation between $A_V$ and $N(Zn II)$ for Mg II-selected systems from York et al. (2006). Their analysis assumed an SMC dust-to-gas ratio. It is worthwhile to re-explore their statement for a higher dust-to-gas ratio as suggested by the present analysis.

5 THE $A_V$–$N_{HI}$ RELATION

As mentioned in the introduction, the Bohlin et al. (1978) relation, $A_V/N_{HI} \approx 5.3 \times 10^{-22}$ mag cm$^2$ has been established from measurements with $E(B–V) > 0$.1 mag. As our statistical approach allows us to be sensitive to reddening values lower by an order of magnitude, it is interesting to investigate the validity of such a relation for (i) lower column densities and (ii) those in extragalactic environments. In Fig. 4, we show measurements of $A_V$ and $N_{HI}$ for lines of sight within our Galaxy from Bohlin et al. (1978) and Snow et al. (2002). The blue data points show our estimates of $A_V$ and the median $N_{HI}$ for three bins of Mg II rest equivalent width. The red points show the same quantity but scaled to $z = 0$ using the star formation weighted metallicity evolution given by Davé & Oppenheimer (2007) and introduced in the previous section. Remarkably, we find that the Bohlin et al. relation between $A_V$ and $N_{HI}$ holds down to substantially lower hydrogen and dust column densities, regardless of ionization corrections. Once evolutionary effects are taken into account, the hydrogen and dust content of strong metal absorbers at $z \sim 1$ appear to be in reasonable agreement with this relation.

6 SUMMARY AND OUTLOOK

The expanded SDSS/HST sample of low-redshift Lyman-α absorbers compiled by Rao et al. (2006) has provided us with the
distribution of hydrogen column densities of strong Mg II absorbers. Using this data set, we have shown that

(i) due to the nature of the distribution (spanning 3 orders of magnitude in \( N_{\text{H}} \)), estimates at a fixed \( W_0 \), the arithmetic mean \( \langle N_{\text{H}} \rangle \) is effectively sensitive to only a few per cents of the systems in a Mg II-selected sample. Even if \( \langle N_{\text{H}} \rangle \) or \( \Omega_{\text{H}} \) is computed from a sample of 200 objects, it effectively suffers from small-number statistics. This fact might be at the origin of the discrepancies in \( \Omega_{\text{H}} \) currently debated in the literature.

(ii) interestingly, despite the large scatter in hydrogen column density at a fixed \( W_0 \), a well-defined relation exists between these two quantities: both the median and the geometric mean of \( N_{\text{H}} \) show, at the 6\( \sigma \)–8\( \sigma \) level, that \( \langle N_{\text{H}} \rangle_{\text{geo}} \propto W_0^{\alpha} \) with \( \alpha \sim 1.8 \) over a decade in Mg II rest equivalent width.

By combining these hydrogen column density estimations with recent reddening measurements from Ménard et al. (2008), we have shown the following.

(i) While the shape of the mean extinction curve of \( z \sim 1 \) Mg II absorbers is consistent with that of the SMC, the inferred dust-to-gas ratio is substantially higher than that of the SMC: \( \langle A_V \rangle / \langle N(\text{H}) \rangle = 3.0 \pm 0.6 \times 10^{-22} \) mag cm\(^2\).

(ii) This dust-to-gas ratio does not strongly depend on \( W_0 \). It varies by less than a factor of 2 for \( 1 < W_0 < 3.3 \) Å and suggests that systems in this range have a similar origin. Such a property contrasts with the sharp decrease of \( d\langle A_V \rangle / dW_0 \) which varies by a factor of \( \sim 30 \) over the same interval. This may be due to a transient nature of the absorbing gas, such as outflows triggered by star formation.

(iii) In addition, assuming proportionality between dust-to-gas ratio and metallicity, we have shown that the redshift evolution of the dust-to-gas ratio of Mg II systems is in agreement with a star formation weighted metallicity estimate (from Davé & Oppenheimer 2007). Our results therefore confirm the connection between the bulk of strong Mg II absorbers and \( L^* \) galaxies from dust-to-gas ratio considerations only.

Interestingly, given that (i) the mean dust-to-gas ratio of these systems does not favour LMC/SMC values and is consistent with that of \( L^* \) as a function of redshift and (ii) the mean impact parameter of Mg II absorbers is about 50 kpc from a \( L^* \) galaxy (Zibetti et al. 2007) strongly suggest that the absorbing gas originates from the nearby \( L^* \) galaxy. Outflowing gas appears as the most simple explanation regarding the nature of the majority of strong Mg II absorbers. An alternative scenario would involve low-metallicity gas originating from dwarf galaxies and experiencing a higher dust-to-neutral gas ratio due to ionization effects. Such a model is however less attractive as it requires ionization effects to coincidentally increase the dust-to-neutral gas ratio to the value of that of a \( L^* \) galaxy.

Our results made use of geometric mean and/or median estimates. They are aimed at representing the bulk of Mg II absorbers and are not sensitive to outliers in the distributions of hydrogen column densities. We have shown that the systems populating the upper part of Fig. 1 and corresponding to DLAs are necessarily less dusty and likely to be less metal-rich than the bulk of Mg II systems indicated by the median track. This illustrates that, even if an overlap exists between the two populations, the majority of DLA-selected or Mg II-selected systems do not probe the same type of structures.

It will be of particular interest to repeat such an analysis for metallicity estimates of absorber systems. In addition, accessing several transitions would allow us to better constrain the ionization fraction.

Finally, we have shown that our measurements allow us to probe the relation between \( A_V \) and \( N_{\text{H}} \), i.e. between dust and hydrogen column densities, in regimes that were previously unexplored. In particular, we have shown that the Bohlin et al. (1978) relation measured from lines of sight in our Galaxy is also satisfied by Mg II absorbers at \( z \sim 1 \), for column densities and reddening values significantly lower than previously probed. As it relates the amount
of dust to the neutral hydrogen column density, this statement is valid regardless of the level of ionization.

If the bulk of Mg II absorbers are tracers of outflowing gas, they may provide us with an interesting view of delayed star formation around galaxies. Assuming a wind velocity of about 300 km s\(^{-1}\), i.e. about 300 kpc Gyr\(^{-1}\), the presence of a strong Mg II absorber is then typically related to a burst of star formation which occurred about 150 Myr ago. The observed properties of Mg II absorption lines (incidence, redshift evolution, velocity width, number of components) can provide us with observational constraints on star formation in the Universe, up to high redshifts where emission studies are more difficult.

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