Mg ii ABSORPTION SYSTEMS WITH $W_0 \geq 0.1$ Å FOR A RADIO SELECTED SAMPLE OF 77 QUASI-STEellar OBJECTS AND THEIR ASSOCIATED MAGNETIC FIELDS AT HIGH REDSHIFT*  

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ABSTRACT  
We present a catalog of Mg ii absorption systems obtained from high-resolution Ultraviolet and Visual Echelle Spectrograph/VLT data of 77 quasi-stellar objects in the redshift range $0.6 < z < 2.0$, and down to an equivalent width $W_0 \geq 0.1$ Å. The statistical properties of our sample are found to be in agreement with those from the previous work in the literature. However, we point out that the previously observed increase with redshift of $\partial N/\partial z$ for weak absorbers pertains exclusively to very weak absorbers with $W_0 < 0.1$ Å. Instead, $\partial N/\partial z$ for absorbers with $W_0$ in the range 0.1–0.3 Å actually decreases with redshift, similar to the case of strong absorbers. We then use this catalog to extend our earlier analysis of the links between the Faraday rotation measure (RM) of the quasars and the presence of intervening Mg ii absorbing systems in their spectra. In contrast to the case with strong Mg ii absorption systems ($W_0 > 0.3$ Å), the weaker systems do not contribute significantly to the observed RM of the background quasars. This is possibly due to the higher impact parameters of the weak systems compared to strong ones, suggesting that the high column density magnetized material that is responsible for the Faraday rotation is located within about 50 kpc of the galaxies. Finally, we show that this result also rules out the possibility that some unexpected secondary correlation between the quasar redshift and its intrinsic RM is responsible for the association of high RM and strong intervening Mg ii absorption that we have presented elsewhere, since this would have produced an equal effect for the weak absorption line systems, which exhibit a very similar distribution of quasar redshifts.  

Key words: galaxies: high-redshift – galaxies: magnetic fields – methods: data analysis – quasars: absorption lines 

Online-only material: high-redshift – galaxies: magnetic fields – methods: data analysis – quasars: absorption lines

1. INTRODUCTION  
Quasar absorption line systems provide a unique tool to study the evolution of galaxies through their lifetime. Since the galaxies associated with such systems are selected by their gas cross section, as compared to their stellar luminosities from multi-broadband imaging techniques, absorption lines provide us with a complementary view on galaxy properties and evolution. One of the best studied population of galaxies is the one selected by the Mg ii absorption doublet $\lambda\lambda 2796.35, 2803.53$ Å. Magnesium is produced by alpha-processes in post-main-sequence stars and, therefore, is abundant in galaxies. In addition, Mg ii doublet is easy to observe because it has a large cross section for absorption, it can be easily identified, and the rest-frame wavelengths $\lambda\lambda 2796.35, 2803.53$ Å are detectable from the ground over the full redshift range $0.3 < z < 2.2$.  

Depending on whether the equivalent width $W_0$ of the Mg ii 2796 Å line is greater or smaller than 0.3 Å, the absorption systems are classified as strong or weak, respectively. The fact that the equivalent width distribution appears to steepen below 0.3 Å lends support to the idea that weak and strong absorbers constitute two distinct populations (Nestor et al. 2005; Narayanan et al. 2007).  

It is well established that if there is a strong Mg ii absorption line, then in almost all cases a galaxy is found within 100 kpc with a median impact parameter of around 50 kpc (Steidel 1995; Churchill et al. 2005; Zibetti et al. 2007; Kacprzak et al. 2008; Chen & Tinker 2008).  

The Mg ii host galaxies are known to span a broad range of optical luminosities (0.1–3.0 $L^*$) and colors (Bergeron & Stasińska 1986; Steidel 1995; Kacprzak et al. 2008). The gas traced by strong Mg ii absorption spans a wide range of neutral hydrogen column densities from $10^{17}$ to $10^{22}$ cm$^{-2}$ (Churchill et al. 2000; Rao et al. 2006). Recently, Ménard & Chelouche (2009) found a strong correlation between the median $N_{HI}$ and the Mg ii rest equivalent width $W_0$. However, the nature of the objects selected by weak Mg ii absorption is not yet completely clear. It has been suggested that they form separate populations of galaxies with respect to those traced by strong absorbers, e.g., low surface brightness galaxies or dwarf galaxies (Churchill et al. 1999; Narayanan et al. 2007). Alternatively, the weak systems could be tracing the same galaxies as the strong absorbers, but at a higher quasi-stellar object (QSO) impact parameter where the gas density is much lower and, hence, the equivalent width is smaller (Churchill et al. 2005; Kacprzak et al. 2008).  

In this paper, we present observations obtained with the Ultraviolet and Visual Echelle Spectrograph (UVES) (Dekker et al. 2000) at the Very Large Telescope (VLT) and the associated catalog of strong and weak Mg ii absorption lines down to an equivalent width limit of 0.1 Å, giving details of the selection criteria and the methods applied. We also construct the inferred number densities of the Mg ii system and the observed equivalent width distribution and compare these with results published in the literature. Compared with most previous surveys for strong Mg ii absorption systems (Lanzetta et al. 1987; Steidel & Sargent 1992; Nestor et al. 2005; Nestor et al. 2006) we have a much higher spectral resolution, $R \approx 43,000$, which allows us to identify the strong Mg ii systems unambiguously.  

In a previous paper, we have used the catalog of strong Mg ii absorbers presented in this paper to probe the magnetic fields in normal galaxies at redshift $z \sim 1$ (Bernet et al. 2008). As we
had already hypothesized in Kronberg et al. (2008) in order to explain the observed increase in QSO rotation measure (RM) as a function of the QSO redshift, in Bernet et al. (2008) we demonstrated that lines of sight with strong Mg ii absorption lines have significantly higher RM than those without. This implies the presence of μG strong, large-scale magnetic fields in the associated galaxies.

In this work, we extend our analysis to weak Mg ii absorption systems with equivalent width in the range 0.1–0.3 Å. We show that unlike their strong counterparts, weak absorbers do not contribute with any significance to the observed RMs. We discuss the possible interpretations of this result. We also show that this result argues against the case in which the correlation between RM and strong Mg ii absorption systems reported in Bernet et al. (2008) arises due to an intrinsic evolution of QSOs magnetic fields.

The paper is organized as follows. In Section 2, we present the Mg ii absorption system catalog, including the details of the observations and data analysis; in Section 3, we analyze the statistical properties of the detected absorption systems and compare them with previous work; in Section 4, we investigate the correlation of the Mg ii system with RM; a short summary in Section 5 concludes the paper.

2. OPTICAL DATA

2.1. Spectra

Our data set consists of 77 QSO spectra obtained with the high-resolution UVES spectrograph at the VLT. The QSOs were selected from the larger sample of 901 radio sources with determined RM and redshifts presented in Kronberg et al. (2008). The selection was based on the following criteria: (1) redshift range 0.6 < zQSO < 2.0, (2) Galactic latitudes |b| > 30°, and (3) m_v < 19. The latter was imposed to have adequate signal-to-noise ratio (S/N) in exposure times up to 30 minutes per object. In order to produce a complete census of strong Mg ii absorption systems in the redshift range 0.35 < z < zQSO, we required an S/N per resolution element S/N ≥ 10, across the full spectral range, although the data quality was typically better than that. To fully cover the redshift path to each QSO we chose the following standard setting of UVES, with dichroic 1 having central wavelengths 390 nm and 580 nm, and dichroic 2 having central wavelengths 437 nm and 760 nm for the blue and red arms, respectively. This results in complete wavelength coverage from 3480 Å to 9460 Å with only two small spectral gaps between 5762–5834 Å and 7513–7660 Å due to the small gap between the two CCDs of the red arm of UVES. We chose a slit width of 1″ corresponding to R ≈ 45,000 and R ≈ 43,000 in the blue arm and red arm, respectively. The observations took place during three nights on 2006 July 28–30 (in visitor mode) and during 30 hr of service mode observations carried out between 2006 October and 2007 April.

2.2. Data Reduction

The spectra were bias subtracted, flat-fielded, and wavelength calibrated using the ESO MIDAS package in the OPTIMAL mode. The reduced one-dimensional vacuum-heliocentric corrected exposures were first scaled to the same flux level and then co-added, weighted by the S/N of the corresponding pixel. The spectra were then normalized using a spline method to fit the continuum. To increase the S/N of the spectra the overlapping wavelength regions of different settings were also co-added.

To detect the absorption lines we used the so-called aperture method (Lanzetta et al. 1987). Namely, we identified strong Mg ii absorption systems by requiring a 3σ detection of the rest-frame equivalent width of the Mg ii λ 2796 Å line. The absorption system was considered a Mg ii absorption identification if there was also at least a 2.5σ detection of the corresponding λ 2803 Å line at the same redshift. We further checked if the doublet ratio, DR = EW_{2803}/EW_{2796}, of the Mg ii lines lay within the range from 1.0 for completely unsaturated lines and 2.0 for saturated lines (within errors). We also visually checked the line system for similar profile shapes to exclude chance alignments. Mg ii systems within 500 km s$^{-1}$ of each other are considered as one single absorption system with the equivalent widths added together. We also visually inspected the flux spectra to look for Mg ii absorption lines that might have been missed by the algorithm. This was twice the case, where the stronger λ2796 Å line was detected as a single absorption line but the weaker λ2803 Å line consisted of two separate lines, with miscalculated centroids.

2.3. Completeness

To check the completeness of our catalog, following Lanzetta et al. (1987) we calculated the redshift path of the survey for a certain equivalent width detection threshold $W_{\text{min}}$. The redshift path is given by

$$\Delta Z(W_{\text{min}}) = \frac{53}{\sigma_{\text{EW}(z)}} \int_{z_{\text{min}}}^{z_{\text{max}}} g_i(W_{\text{min}}, z)dz, \quad (1)$$

where

$$g_i(W_{\text{min}}, z) = H(z - z_i) H(z_i - z) \times H(W_{\text{min}} - N \sigma_{\text{EW}(z)}/(1 + z)), \quad (2)$$

is 1 if the Mg ii λ λ 2796,2803 doublet could have been detected at redshift $z$ with a rest-frame equivalent width greater or equal to $W_{\text{min}}(2796)$ at a significance level greater than $N_\sigma$, and zero otherwise. In Equation (2), $H()$ is the Heavyside function, $z_{\text{min}}$ and $z_{\text{max}}$ are the minimum and maximum redshifts observed for the ith QSO, that is 0.345 and the quasar redshift, $z_{\text{QSO}}$, respectively. Also, $\sigma_{\text{EW}(z)}$ is the Poisson error on the equivalent width per resolution element at redshift $z$.

The redshift path of the survey $\Delta Z$ as a function of the equivalent width limit $W_{\text{min}}$ is shown in Figure 1. It can be seen that the redshift path begins to fall below 0.1 Å but is nearly constant above, showing that our sample has a high completeness down to $W_{\text{min}} \geq 0.1$ Å. Finally, the drop in $\Delta Z$ at $W_{\text{min}} = 0.3$ Å is because for the weak Mg ii systems we excluded spectral ranges known for atmospheric absorption from the search.

We miss only about $\Delta Z = 1.5$ of the total available redshift range between $z = 0.345$ and the quasar redshifts $z_{\text{QSO}}$ (due to the two small spectral gaps). This leads to a high completeness of the redshift coverage of 97% at $W_{\text{min}} = 0.3$ Å and 92% at $W_{\text{min}} = 0.1$ Å.

2.4. Mg ii Absorbers Catalogs

Our sample includes a total of 44 strong Mg ii absorption systems with mean redshift $(z_{\text{Mg}^\prime}) = 0.85$ and a total redshift path of $\Delta Z = 55.8$, and 44 weak Mg ii systems in the equivalent width range 0.1–0.3 Å, with a redshift path of $\Delta Z = 53.0$. The
complete catalog of detected strong Mg II absorption systems is presented in Table 1. However, Mg II absorption lines lying within 3000 km s$^{-1}$ of the quasar redshift, i.e., arising in the environment local to the QSO, were excluded in any further analysis to maintain the sample of Mg II host galaxies as homogenous as possible. When multiple systems of absorbers are detected along the line of sight to the same QSO, the remaining observed lines of sight are reported in Table 3.

2.5. Note on the QSO PKS 2353−68

The high redshift QSO PKS 2353−68 is part of our sample and the optical spectra allowed us to make an independent estimate of its redshift, which disagrees with the value of $z = 1.716$ from the Hewitt & Burbidge (1989) optical catalog. In fact, the radio emission of this QSO is centered on R.A. (1950): 23:53:22.9, decl. (1950): $-68:36:46$ (PKS catalog, Gregory et al. 1994) and the optical spectrum associated to these coordinates shows broad Lyα emission at 4580 Å. This corresponds to a redshift $z \approx 2.77$, see Figure 2. Further investigation suggests that the object at $z = 1.716$ reported by Hewitt & Burbidge is actually 115″ away at R.A. (1950): 23:53:28.3, decl. (1950): $-68:35:24$ (Hewitt & Burbidge 1989).

3. Mg II ABSORBERS STATISTICS

3.1. Redshift Number Density

The number densities of strong Mg II absorption systems, $\partial N/\partial z$, are simply defined as

$$\partial N/\partial z = N/\Delta z,$$

where $N$ is the number of absorbers in the redshift interval, $\Delta z$. The errors on the number density are given by Poisson statistics, namely

$$\sigma_{\partial N/\partial z} = \sqrt{N/\Delta z}.$$  

Figure 3 shows $\partial N/\partial z$ as measured from our data (black open squares) as a function of redshift, for three different values of the equivalent width, $W_0$. Our results are found to be consistent with those of Nestor et al. (2005, NTR05) from the Sloan Digital Sky Survey (red filled circles) in the redshift range $z = 0.4−2.0$. In particular, we find an almost constant $\partial N/\partial z \simeq 0.80 \pm 0.12$ at a mean redshift of $\langle z_{\text{MgII}} \rangle = 0.85$, to be compared with $\partial N/\partial z \simeq 0.783 \pm 0.033$ at a mean redshift of $\langle z_{\text{MgII}} \rangle = 1.11$, of NTR05 (see Table 4). Overplotted as dashed lines in Figure 3 are the redshift number densities for a concordance ΛCDM universe with parameters ($\Omega_m, \Omega_L, h = (0.27, 0.73, 0.7$). In these no-evolution curves (NECs), we assume a constant comoving number density and a comoving cross-sectional area proportional to $(1+z)^2$. Note that in the equivalent width range $0.3 \leq W_0 < 0.6$ Å the data also suggest an upturn of $\partial N/\partial z$ compared with the NEC in the lowest redshift bin $z \approx 0.5$ which NTR05 sees at 3σ.

Turning to the weak Mg II absorption systems in Figure 4, we compare our results for $\partial N/\partial z$ with those of Churchill et al. 1999 (CRCV99), who looked for weak Mg II absorption lines in High Resolution Echelle Spectrometer/Keck spectra of 26 QSOs in the redshift range 0.4−1.4, and Narayan et al. 2007 (NMCT07), who carried out a survey for weak Mg II absorbers using UVES/VLT archive data of 81 QSOs in the redshift range 0.4−2.4. In both works, the $\partial N/\partial z$ are given for the equivalent width range $0.0165 \leq W_0 < 0.3$ Å. Therefore, to compare with our result in the equivalent width range 0.1−0.3 Å we split their samples in two bins and recomputed the $\partial N/\partial z$ for the bins 0.0165−0.1 Å and 0.1−0.3 Å. The evolution of $\partial N/\partial z$ as a function of redshift for these two bins is shown in Figure 4 and the values of $\partial N/\partial z$ are summarized in Table 5.

Using the entire range of weak equivalent widths, both CRCV99 and NMCT07 found a significant increase in $\partial N/\partial z$ from redshift 0.4 to 1.4. However, after splitting in the two equivalent width bins reported in Figure 4, we find that this behavior is dominated by systems in the equivalent width range $0.0165−0.1$ Å. In this range $\partial N/\partial z$ increases from $0.43 \pm 0.25(0.29 \pm 0.17)$ to $1.23 \pm 0.36(0.78 \pm 0.14)$ from a mean redshift of $\langle z_{\text{MgII}} \rangle = 0.59(0.57)$ to $\langle z_{\text{MgII}} \rangle = 0.98(1.07)$ for the data of CRCV99 (NMCT07).

In the equivalent width range 0.1−0.3 Å and in the redshift range 0.4−1.4, we find that $\partial N/\partial z$ decreases toward higher redshifts from $0.94 \pm 0.21$ at a mean redshift $\langle z_{\text{MgII}} \rangle = 0.53$ to $0.65 \pm 0.16$ at $\langle z_{\text{MgII}} \rangle = 0.90$. This finding is supported by our re-analysis of the CRCV99 data which gives a decrease of $\partial N/\partial z$ of $1.00 \pm 0.38$ at $\langle z_{\text{MgII}} \rangle = 0.60$ to $0.71 \pm 0.27$ at $\langle z_{\text{MgII}} \rangle = 1.09$. The data of NMCT07 rather favor a flat $\partial N/\partial z$ with $\partial N/\partial z = 0.77 \pm 0.27$ at $\langle z_{\text{MgII}} \rangle = 0.53$ and $\partial N/\partial z = 0.87 \pm 0.15$ but the data within the error bars are also still consistent with a decrease toward higher redshifts.

Assuming a power law of the form $\partial N/\partial z = N_0(1+z)^\gamma$ for the redshift distribution of weak absorbers, a formal $\chi^2$ fit leads to best-fit parameters $N_0 = 2.25^{+2.85}_{-1.35}$ and $\gamma = -1.9^{+1.7}_{-1.6}$. Thus, our observation suggests that for $z < 1.0$ we see an upturn in the $\partial N/\partial z$ for $0.1 \leq W_0 < 0.3$ Å analog to the one seen for the equivalent width range $0.3 \leq W_0 < 0.6$ Å.

3.2. Equivalent Width Distribution

In Figure 5, the distribution of the rest-frame equivalent widths of the Mg II systems is presented. Steidel & Sargent 1992...
Table 1

| QSO       | $z_{\text{QSO}}$ | R.A. (12000) | Decl. (12000) | $z_{\text{Mg}^\text{II}}$ | $W_0(2796)$ ($\AA$) | $z_{\text{Mg}^\text{II}}$ | $W_0(2796)$ ($\AA$) |
|-----------|------------------|--------------|---------------|-------------------|---------------------|-------------------|---------------------|
| PKS1244−255 | 0.638  | 12:46:46.8 | −25:47:49 | 0.49236 | 0.68  |
| OX−192    | 0.672  | 21:58:06.3 | −15:01:09 | 0.63205 | 1.40  |
| 4C+19.44  | 0.72   | 13:57:04.4 | +19:19:07 | 0.45653 | 0.85  |
| OC−65     | 0.733  | 01:41:25.8 | −09:28:44 | 0.50046 | 0.53  |
| 4C+19.34  | 0.828  | 10:24:44.8 | +19:12:20 | 0.52766 | 1.00  |
| PKS0420−01| 0.915  | 04:23:15.8 | −01:20:33 | 0.63291 | 0.77  |
| 3C336a    | 0.9274 | 16:24:39.1 | +23:45:12 | 0.47192 | 0.93  |
| PKS2354−11a | 0.96   | 23:57:31.2 | −11:25:39 | 0.54456 | 0.53  |
| PKSB1419−272 | 0.985 | 14:22:49.2 | −27:27:56 | 0.55821 | 0.44  |
| 4C+6.69   | 0.99   | 21:48:05.4 | +06:57:39 | 0.79086 | 0.55  |
| 4C+01.24  | 1.018  | 09:09:10.1 | +01:21:36 | 0.53587 | 0.44  |
| PKS0130−17| 1.022  | 01:32:43.5 | −16:54:49 | 0.50817 | 0.59  |
| 4C−02.55  | 1.045  | 12:32:00.0 | −02:24:05 | 0.39524 | 2.03  |
| MRC0122−003 | 1.07  | 01:25:28.8 | −00:05:56 | 0.39943 | 0.47  |
| PKS0506−61 | 1.093 | 05:06:43.9 | −61:09:41 | 0.92269 | 0.49  |
| PKS0426−380c | 1.11  | 04:28:40.4 | −37:56:20 | 0.55855 | 0.93  |
| 3C208     | 1.11   | 08:53:08.8 | +13:52:55 | 0.65262 | 0.62  |
| 4C+13.46  | 1.141  | 12:13:32.1 | +13:07:21 | 0.77189 | 1.29  |
| PKS0038−020 | 1.178 | 00:40:57.6 | −01:46:32 | 0.68271 | 0.35  |
| PKS2204−54 | 1.206 | 22:07:43.7 | −53:46:34 | 0.6877  | 0.73  |
| 4C+06.41  | 1.27   | 10:41:17.1 | +06:10:17 | 0.44151 | 0.69  |
| PKS0839−18 | 1.27  | 08:42:05.1 | +18:35:41 | 0.71118 | 0.56  |
| PKS2326−477 | 1.299 | 23:29:17.7 | −47:30:19 | 0.43195 | 0.38  |
| PKS1615+029 | 1.339 | 16:17:49.9 | +02:46:43 | 0.52827 | 0.31  |
| PKS0112−017 | 1.365 | 01:15:17.1 | −01:27:05 | 1.18965 | 0.90  |
| PKS2223−05 | 1.404 | 22:25:47.2 | −04:57:01 | 0.84652 | 0.60  |
| PKS0402−362 | 1.417 | 04:03:53.7 | −36:05:02 | 0.79688 | 1.80  |
| PKS0332−403 | 1.445 | 03:34:13.7 | −40:08:25 | 1.20898 | 0.79  |
| OQ+135    | 1.611  | 14:23:30.1 | +11:59:51 | 1.36063 | 0.51  |
| OX+57     | 1.932  | 21:36:38.6 | +00:41:54 | 0.62855 | 0.60  |
| OW−174    | 1.932  | 20:47:19.7 | −16:39:06 | 1.32871 | 0.61  |
| PKS1143−245 | 1.95  | 11:46:08.1 | −24:47:33 | 1.24514 | 0.30  |
| 4C+5.81a  | 1.967  | 21:53:24.7 | +05:36:19 | 1.88286 | 0.89  |
| PKS1157+014 | 1.986 | 11:59:44.8 | +01:12:07 | 1.94372 | 1.58  |
| PKS2353−68 | 2.77   | 23:56:00.7 | −68:20:03 | 1.26958 | 0.40  |

Notes. Column 1: name of the source, Column 2: redshift of the source, Columns 3 and 4: coordinates, Column 5: redshifts of the systems with strong Mg II absorption, Column 6: equivalent widths $W_0(2796)$ of the strong Mg II absorption systems, Column 7: redshifts of the systems with weak Mg II absorption, Column 8: equivalent widths $W_0(2796)$ of the weak Mg II absorption systems.

* Sources were not included in the work of Bernet et al. (2008) because optical and radio emission are separated by more than 5 km/s.

* Source was not included in the work of Bernet et al. (2008) due to Mg II absorption local to the QSO at $z_{\text{Mg}^\text{II}} = 0.9587$ with $W_0 = 0.61$.

* This source was not used in Bernet et al. (2008) due to a misidentification.

(SS92) found that the number of Mg II absorption systems with rest equivalent width $W_0(2796)$ per unit equivalent width per unit redshift can be either described by an exponential distribution of the form:

$$ \frac{\partial N}{\partial W_0} = \frac{N^*}{W^*} e^{-W_0/W^*}, $$

(5)
with free parameters $N^*$ and $W^*$, or by a power-law distribution of the form:

$$\frac{\partial N}{\partial W_0} = CW_0^{-\delta},$$

with free parameters $C$ and $\delta$.

Using the maximum-likelihood method SS92 determined the parameters as $N^* = 1.55 \pm 0.20$, $W^* = 0.66 \pm 0.11$ and $C = 0.38 \pm 0.03$, $\delta = 1.65 \pm 0.09$ at a mean redshift of the absorbers of $\langle z_{\text{Mg}\ II}\rangle = 1.12$. However, they noted that an exponential distribution underpredicts the number of weak systems (here $W_0 < 0.5$ Å), whereas a power-law fit overpredicts the number of intermediate systems (here $0.7 \lesssim W_0 < 1.3$ Å).

Our maximum likelihood fit of a single exponential function to Mg II systems with $W_0 > 0.3$ Å gives best-fit parameters of $W^* = 0.74_{-0.14}^{+0.19}$ Å and $N^* = 1.18 \pm 0.33$. This is in very good agreement with the tightly constrained parameters of NTR05 with $W^* = 0.702 \pm 0.017$ Å and $N^* = 1.187 \pm 0.052$ using over 1300 Mg II doublets. The values are summarized in Table 6.

For the equivalent width range $0.1 \rightarrow 0.3$ Å we can additionally compare the $\partial N/\partial W_0$ with the results of CRCV99 and NMCT07 which both give $\partial N/\partial W_0$ in the redshift range 0.4--1.4. Below 0.3 Å the equivalent width distribution distinctly rises above the single exponential fit for $W_0 \geq 0.3$ Å as previously seen by Nestor et. al. (2006) and NMCT07. This is further shown in the inset of Figure 5 where the red dashed line corresponds to the best fit to systems with $W_0 > 0.3$ Å by NTR05. Note that there is a slight discrepancy between NMCT07 and CRCV99.
in that CRCV99 finds systematically more Mg ii systems in all three plotted equivalent width bins ([0.0165,0.1], [0.1,0.2], [0.2,0.3] Å). For the lowest equivalent width bin, centered at 0.06 Å, this is the level of 1.8σ. Unfortunately, we are unable to make a statement about the discrepancy because our redshift path falls dramatically in this equivalent width bin.

4. ROTATION MEASURE DATA

4.1. Dependence of Rotation Measure Distributions on Equivalent Width Detection Threshold

Bernet et al. (2008) showed that the RM distribution function, for lines of sight with strong Mg ii absorption lines, is significantly broader than those without such lines. This led those authors to conclude that there must exist substantial magnetized plasma in or near the absorption line systems. It is unclear at this stage whether the association is direct, or whether the Mg ii absorption merely indicates that the quasar sightline passes through a galactic halo. Regardless, this result suggests the presence of μGauss-level large-scale magnetic fields in or around typical galaxies when the universe was a half or less of its current age, with important implications for our understanding of the development of magnetic fields in galaxies, and in particular setting interesting constraints on the required efficiency of the conventional galactic dynamo model.

Since our catalog of Mg ii absorption systems is complete down to 0.1 Å, we can now repeat the analysis of Bernet et al. (2008) and test their result versus the applied equivalent width detection threshold of Mg ii absorbers. This would clarify whether or not weak Mg ii systems also have large-scale magnetic fields that contribute to the observed RM.

Figure 6 compares the RM cumulative distribution functions having $N_{Mg\,\text{ii}} = 0$, $>0$, and >1, where $N_{Mg\,\text{ii}}$ refers to the number of strong and weak Mg ii absorption lines for the left and right panels, respectively. The left panel is the result already presented in Bernet et al. (2008). For this panel, a Kolmogorov–Smirnov test indicates that the RM distributions for $N_{Mg\,\text{ii}} = 0$, $N_{Mg\,\text{ii}} > 0$ are different at the 94.5% significance level and those for $N_{Mg\,\text{ii}} = 0, N_{Mg\,\text{ii}} > 1$ at the 99.98% significance level. Given that we were testing a specific hypothesis in a clean way with completely independent observational data, we regard this result as significant. On the other hand, the right panel was built using the weak Mg ii absorbers catalog of this paper (including here also the eight systems below $W_0 < 0.1$ Å) and the same RM data as in Bernet et al. (2008). Note that in this case $N_{Mg\,\text{ii}} = N_w$, which does not account for the number of strong Mg ii absorption lines along the lines of sight. A KS-test does not recognize any difference in the RM distribution functions for $N_{Mg\,\text{ii}} = 0, > 0$ with a significance level of 22.1% and 31.0% for $N_{Mg\,\text{ii}} = 0, > 1$. Since the RM distributions look statistically equivalent independent of the number of weak Mg ii absorption systems, it is immediately clear that the weak Mg ii absorption system contribution to the observed QSO RM must be negligible.

This result was also hinted at in observed redshift dependence of the RM distribution (see Kronberg et al. 2008). In that work, our analysis was based solely on the RM distribution of 268 quasars in the range $0 < z_{QSO} < 3.0$, without any spectroscopic information. It was noted that the observed increase in the width of the RM distribution with redshift was better reproduced by a simple model in which the statistics of the interveners was given by the relatively rare strong Mg ii

![Figure 3. Number densities of strong Mg ii absorption systems as a function of redshift obtained in this survey (black open squares) for different equivalent width ranges. Overplotted as dashed lines are the NECs, scaled with a $\chi^2$ fit to the observed redshift number densities. For comparison the number densities of Nestor et al. (2005) are plotted as red solid circles (NTR05). Horizontal error bars give the bin sizes.](image)

![Figure 4. Number densities of weak Mg ii absorption systems as a function of redshift for the equivalent width ranges 0.0165–0.1 Å and 0.1–0.3 Å. The values obtained in this work are shown by black open squares. For comparison the results of Churchill et al. (1999; CRCV99) and Narayanan et al. (2007; NMCT07) are overplotted as green empty triangles and blue crosses, respectively. Horizontal error bars give the bin sizes.](image)

![Table 4 Number Densities of Strong Mg ii Absorption Systems](image)
RM distribution already starts at $z$ at low redshifts in this model, the increase in the width of the absorption systems. Due to the increased number of intervenors systems than by one which included also the commoner weaker absorption systems. As pointed out in Bernet et al. (2008), because the probability of intercepting a Mg $\text{II}$ absorber along the line of sight (l.o.s.) increases strongly with the QSO redshift, a strong evolution of the magnetic fields local to the QSOs could give rise to a fictitious correlation of [RM] with the number of strong Mg $\text{II}$ absorption lines. The evolution in the magnetic fields local to the QSOs would have to be significant in order to produce the observed increase in RM dispersion with $z$ despite the strong $\propto (1 + z)^{-2}$ "k-correction" in the observed RM, due to the $\lambda^{-2}$ dependence of the RM.

By comparing the median of the [RM] distribution of l.o.s. with and without strong Mg $\text{II}$ absorption for different QSO redshifts, Bernet et al. (2008) found that there is only a 7% chance probability that their result was due to the above spurious correlation or, in general, to a correlation between redshift and [RM].

Our new demonstration above that sightlines with weak Mg $\text{II}$ absorption do not show statistically enhanced [RM] values, can be used as an even more convincing test to rule out the possibility that an underlying correlation between [RM] and $z_{\text{QSO}}$ causes the observed RM broadening at high redshifts. In the left-hand panel of Figure 7, the redshift distributions for the QSOs whose sightlines do and do not exhibit strong Mg $\text{II}$ absorption systems are shown as red and black shaded histograms. The same is shown in the right-hand panel for the weak Mg $\text{II}$ absorption systems. Apparently the QSO redshift distributions are very similar independent of whether the Mg $\text{II}$ absorption systems belong to the weak or strong category. A KS-test reveals no difference between them with a significance level of 1.21% for sightlines with weak and strong Mg $\text{II}$ absorption systems and 0.01% for sightlines without weak or strong Mg $\text{II}$ absorption systems.

### Table 5

| $W_0^{2796}$ \& $z$ Range | This Work $\langle \frac{\partial N}{\partial z} \rangle$ | CRCV99 $\langle \frac{\partial N}{\partial z} \rangle$ | NMCT07 $\langle \frac{\partial N}{\partial z} \rangle$ |
|-----------------------------|---------------------------------|-------------------|-------------------|
| $0.0165 \, \AA \leq W_0^{2796} < 0.1 \, \AA$, $0.4 \leq z < 0.7$ | $0.59 \pm 0.25$ | $0.73 \pm 0.25$ | $0.57 \pm 0.29$ |
| $0.0165 \, \AA \leq W_0^{2796} < 0.1 \, \AA$, $0.7 \leq z < 1.4$ | $0.98 \pm 0.36$ | $1.07 \pm 0.36$ | $1.07 \pm 0.36$ |
| $0.1 \, \AA \leq W_0^{2796} < 0.3 \, \AA$, $0.4 \leq z < 0.7$ | $0.60 \pm 0.38$ | $0.53 \pm 0.37$ | $0.77 \pm 0.27$ |
| $0.1 \, \AA \leq W_0^{2796} < 0.3 \, \AA$, $0.7 \leq z < 1.4$ | $1.09 \pm 0.27$ | $1.06 \pm 0.27$ | $1.06 \pm 0.27$ |

**Notes.** Redshift number densities $\partial N/\partial z$ of weak Mg $\text{II}$ absorption systems for this work and the surveys of Churchill et al. (1999; CRCV99) and Narayanan et al. (2007; NMCT07). In these works, $\partial N/\partial z$ are given for the equivalent width range $0.0165 \leq W_0^{2796} < 0.3$ Å. Values of $\partial N/\partial z$ given here for the two equivalent widths bins are computed values which assume the same redshift path for the two equivalent width ranges as for the whole range. This leads to small underestimates of $\partial N/\partial z$ in the equivalent width range $0.0165 \leq W_0^{2796} < 0.1$ and small overestimates of $\partial N/\partial z$ in the range $0.1 \leq W_0^{2796} < 0.3$ (2–4% in $\partial N/\partial z$).

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**Figure 5.** Rest-frame equivalent width distribution function $\frac{\partial N}{\partial W}$, which is the number of Mg $\text{II}$ absorption systems with rest-frame equivalent width $W_0(2796)$ per unit equivalent width per unit redshift, derived in this survey (black open squares). Overplotted with red solid circles is the equivalent width distribution function from Nestor et al. (2005; $W_0 \geq 0.3$ Å) and Nestor et al. (2006; $W_0 < 0.3$ Å). For the weak absorbers also the results of Churchill et al. (1999; CRCV99) and Narayanan et al. (2007; NMCT07) are shown as green triangles and as blue crosses, respectively. The red dashed line shows the fit of Nestor et al. (2005) of the form $\frac{\partial N}{\partial W} = N^* e^{-W/W^*}$ with $N^* = 1.187$ and $W^* = 0.702$ to the systems with $W_0 \geq 0.3$ Å.

(A color version of this figure is available in the online journal.)

4.2. Further Evidence that Strong Mg $\text{II}$ Systems are Responsible for the Broadening of the RM Distribution with $z$

As pointed out in Bernet et al. (2008), because the probability of intercepting a Mg $\text{II}$ absorber along the line of sight (l.o.s.) increases strongly with the QSO redshift, a strong evolution of the magnetic fields local to the QSOs could give rise to a
The cumulative [RM] distributions for different number of Mg ii systems in Figure 6 look, however, very different, depending on whether they are selected according to the presence of strong or weak Mg ii systems. There is a clear broadening of the [RM] distribution with increasing number of strong Mg ii absorption lines $N_{\text{str}}$. However, there is virtually no difference in the [RM] distributions for different numbers of weak absorbers $N_{\text{weak}}$. This rules out the possibility that the correlation between [RM] and the number of strong Mg ii absorption lines observed in Bernet et al. (2008) is due to an underlying correlation between [RM] and $z_{\text{QSO}}$.

Figure 8 shows further evidence that the broadening in the RM distribution with redshift is caused by the magnetic fields traced by strong Mg ii systems. The left-hand panel compares the cumulative RM distribution function for QSO from our entire sample with $z \geq 1.0$ and $z < 1.0$. It clearly shows that the high redshift distribution function is broader with respect to the low redshift counterpart. This is most likely due to the fact that the chances of intercepting Mg ii absorption systems are higher at higher redshifts. In fact, as we take out the lines of sight containing strong Mg ii absorbers, the two distributions do not show significant differences anymore (right panel). For the lines of sight without strong Mg ii absorbers, the median [RM] for both low ($z_{\text{QSO}} = 0.79$) and high redshifts ($z_{\text{QSO}} = 1.42$) is around 20 rad m$^{-2}$. This suggests that the I.o.s. without strong Mg ii absorption systems (39 QSOs) are dominated by contributions from magnetic fields within the Milky Way, which is about 20 rad m$^{-2}$ (Bernet et al. 2008).

Any extragalactic RM contributions which increase with $z$, e.g. intergalactic magnetic fields, involving RM contributions local to the QSO, are probably swamped by the Galactic one. It is interesting to note that all four [RM] values with [RM] $> 100$ rad m$^{-2}$ are at $z < 1.0$. This might be partially explained by the fact that a RM contribution local to a QSO at redshift $z_{\text{QSO}}$ is reduced by a factor $(1 + z_{\text{QSO}})^{-2}$ when transformed to the observer’s frame. Thus (non-evolving) RM contributions local to the QSO might just fall below the Galactic contribution at significantly higher redshifts than 1.

4.3. Why do Strong Mg ii Systems Contribute to the Observed Rotation Measure and Weak Ones do not?

In order to address the question of why weak absorbers do not contribute to the RM of distant QSOs, it is important to understand the nature of the weak Mg ii absorbers systems. It has been proposed that these systems are associated with low surface brightness galaxies (Churchill & Le Brun 1997), intergalactic star forming pockets (Rigby et al 2002) or dwarf galaxies (Zonak et al. 2004). More recent works (Churchill et al. 2005; Kacprzak et al. 2008), however, indicate that for some fraction of the weak Mg ii systems a normal ($L = 0.1 - 10L_\odot$) associated galaxy can be found. The impact parameters of the seven weak Mg ii system where Churchill et al. (2005) have Hubble Space Telescope (HST) imaging range from 35 to 115 kpc. It still needs to be sorted out how this is consistent with the general picture that weak Mg ii systems are sub-Lyman Limit systems.

The lack of quantitative knowledge about the fraction of weak Mg ii systems that can be associated with normal galaxies like the ones traced by the strong systems makes it hard to draw strong conclusions from our observation. We need to have more knowledge about the differences in the impact parameter distribution of the galaxies traced by the strong and weak systems and their properties, e.g., luminosity, color. The work of Chen & Tinker (2008) shows that the impact parameters of the galaxies traced by the weak absorbers are generally larger than those traced by the strong systems; they find a moderate anticorrelation between the equivalent width of the identified Mg ii systems and the impact parameters of the galaxies at the 97% level. An inspection of the impact parameters in Chen & Tinker (2008) shows that the median impact parameters of the weak absorbers are around $D \approx 60$ kpc whereas $D \approx 40$ kpc for the strong absorbers.

It is thus plausible that the weak systems are preferentially produced by I.o.s. through the outer regions of a galaxy. Since $\text{RM} \propto n_e B$, with $n_e$ being the density of free electrons and $B$ the magnetic field along I.o.s., we also expect any RM contribution to decline quite rapidly with impact parameter. For strong absorption systems, it has been suggested that on average larger equivalent widths (i.e., stronger absorbers) correspond to galaxies with bluer spectra and smaller impact parameters (Zibetti et al. 2007). If this trend was found to also extend to the weak absorbers, one could also attribute the presence of weaker...
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Concerning the weak absorption systems, we point out that the previously observed increase with redshift of $\partial N/\partial z$ (CRCV99; NMCT07), pertains only to the very weak absorbers with $W_0 < 0.1$ Å. Instead, $\partial N/\partial z$ for absorbers with $W_0$ in the range $0.1–0.3$ Å actually decreases, similarly to the case of strong absorbers.

We use this catalog to extend our previous analysis of the connection between the presence of intervening absorption and the Faraday RM of the quasar. We show that unlike strong Mg $\text{II}$ systems, weak Mg $\text{II}$ absorbers do not contribute to the observed RM. This is likely due to the higher impact parameters of, and/or to lower star formation activity systems traced by, the weak absorbers with respect to strong ones. We use the lack of correlation of RM with number of weak Mg $\text{II}$ absorbers to rule out the possibility that the correlation of RM with number of strong Mg $\text{II}$ absorbers observed in Bernet et al. (2008) is due to an underlying correlation of RM with redshift, caused, for example, by strong evolution of the magnetic field local to the QSOs environments.

We also show that while the distribution of RM for QSOs above $z = 1$ is distinctly broader than the corresponding distribution for QSOs with $z < 1$, the difference disappears once the lines of sight exhibiting Mg $\text{II}$ absorption are removed. This further shows that (a) the increase in the width of the RM distribution with redshift is indeed caused by large-scale magnetic fields traced by strong Mg $\text{II}$ systems, and (b) that any further extragalactic RM contribution is most likely swamped by local Milky Way foreground contributions.

5. SUMMARY

We have presented a catalog of strong and weak Mg $\text{II}$ absorption systems with equivalent width down to 0.1 Å, obtained from a survey of 77 QSOs using the UVES spectrograph at the VLT. We determine the statistical properties of strong Mg $\text{II}$ systems and find them in good agreement with previous results. In particular, we confirm the upturn in $\partial N/\partial z$ at lower redshifts ($z < 0.6$) for systems in the equivalent width range $0.3 \leq W_0 < 0.6$ Å. Compared with no-evolution models in a $\Lambda$CDM universe we find more Mg $\text{II}$ systems at lower redshifts.

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