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Strong Mg II and Fe II Absorbers at $2.2 < z < 6.0$

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Abstract

We present a study of strong intervening absorption systems in the near-IR spectra of 31 luminous quasars at $z > 5.7$. The quasar spectra were obtained with Gemini GNIRS that provide continuous wavelength coverage from $\sim 0.9$ to $\sim 2.5 \mu m$. We detect 32 strong Mg II doublet absorbers with rest-frame equivalent width $W_r(\lambda 2796) > 1.0$ Å at $2.2 < z < 6.0$. Each Mg II absorber is confirmed by at least two associated Fe II absorption lines in the rest-frame wavelength range of $\sim 1600$–$2600$ Å. We find that the comoving line density ($dn/dX$) of the strong Fe II-bearing Mg II absorbers decreases toward higher redshift at $z > 3$, consistent with previous studies. Compared with strong Mg II absorbers detected in damped Ly$\alpha$ systems at $2 < z < 4$, our absorbers are potentially less saturated and show much larger rest-frame velocity widths. This suggests that the gas traced by our absorbers is potentially affected by galactic superwinds. We analyze the Hubble Space Telescope near-IR images of the quasars and identify possible associated galaxies for our strong absorbers. There are a maximum of two galaxy candidates found within 5″ radius of each absorber. The median F105W-band magnitude of these galaxy candidates is 24.8 mag, which is fainter than the $L^*$ galaxy luminosity at $z \sim 4$. By using our observed $dn/dX$ of strong Mg II absorbers and galaxy candidates median luminosity, we suggest that at high redshift, strong Mg II absorbers tend to have a more disturbed environment but smaller halo size than that at $z < 1$.

Unified Astronomy Thesaurus concepts: Circumgalactic medium (1879); Extragalactic astronomy (506); Quasar absorption line spectroscopy (1317)

1. Introduction

The circumgalactic medium (CGM) is defined as the gas around the disk or interstellar medium of a galaxy typically within the virial radius of the galaxy. Previous studies suggested that the physical conditions of the gas in the CGM are influenced by both cold accretion inflows and galactic outflows (see Tumlinson et al. 2017 for a review and references therein). Studies of absorption lines toward bright background sources such as quasars provide a unique and powerful tool to study the physical conditions of the gas. Among these absorption lines, the low-ionization Mg II $\lambda \lambda 2796, 2803$ doublet is found to be associated with cool components ($T \sim 10^4$ K) in CGM (Bergeron & Boisson 1991; Steidel et al. 2002). Observationally, the connection between the Mg II absorption and CGM is studied using quasar–galaxy pairs at low redshift. By comparing the kinematics of absorbers and galaxies, Mg II has been shown to trace both metal-enriched infalling gas (Chen et al. 2010; Lovegrove & Simcoe 2011; Kacprzak et al. 2011; Rubin et al. 2012; Bouché et al. 2013; Zabl et al. 2019), and outflows from luminous star-forming galaxies (Bouché et al. 2006; Martin & Bouché 2009; Noterdaeme et al. 2010; Ménard & Fukugita 2012; Schroetter et al. 2016, 2019). Zabl et al. (2019) studied nine quasar–galaxy pairs that were selected from 79 Mg II absorbers at $z \sim 1$. They found that the halo gas probed by Mg II lines is approximately aligned with the galaxy’s angular momentum vector, which suggests that the Mg II gas co-rotates with galaxy disks. Using the same catalog of Mg II absorbers, Schroetter et al. (2019) selected 26 quasar–galaxy pairs and studied their azimuthal angle, which is the angle between the galaxy’s major axis and quasar location (see e.g., Zabl et al. (2019) Figure 1). The bimodality of azimuthal angles suggests that the outflows are bi-conical in nature.

Strong Mg II systems, defined by their rest-frame equivalent width $W_r$, are found to trace cosmic star formation rate (SFR; Ménard et al. 2011). Observations have shown that Mg II absorbers are associated with a large amount of neutral gas (Lanzetta et al. 1987; Steidel et al. 1995, 1997; Rao et al. 2006; Nestor et al. 2007). Rao et al. (2006) studied 197 Mg II systems and their H I profiles at 0.11 < $z$ < 1.65 using Hubble Space Telescope (HST) UV spectroscopy. Their results show that all the damped Ly$\alpha$ (DLA) systems (log $N$(H I) [cm$^{-2}$] > 20.3) have $W_r(\lambda 2796) > 0.6$ Å. As DLA systems are regarded as the progenitors of star-forming galaxies today, consequently, strong Mg II absorption systems are thought to be correlated with star formation as well. As pointed out in Matejek & Simcoe (2012, hereafter M12), systems traced by strong Mg II absorbers tend to belong to galaxies with high SFRs. In the
literature, some studies define systems with \( W_r(\lambda 2796) > 0.3 \) Å as strong systems, while others use \( W_r(\lambda 2796) > 1.0 \) Å. In this paper, we use the latter as the definition of strong Mg II absorbers.

To trace star formation with strong Mg II absorption systems, the first parameter to calculate is the pathlength number density. The pathlength can be redshift \((dz)\) or comoving pathlength \((dX)\), for which

\[
X(z) = \int_0^z (1 + z')^2 \frac{H_0}{H(z')} dz'.
\]

The number of absorbers per unit redshift (per absorption distance) \( dN/dz \) \((dN/dX)\) has been studied in strong Mg II systems at low to high redshift. The evolution of the comoving line density \( dN/dX \) is above and beyond passive evolution due to the expansion of the universe. At \( z < 2 \), Zhu & Ménard (2013) found that the \( dN/dz \) of Mg II absorbers rises with increasing redshift. At \( z > 2 \), M12 and Chen et al. (2017; hereafter C17) show that the comoving \( dN/dz \) of strong Mg II \((W_r > 1 \) Å\) decreases with increasing redshift, by analyzing 110 absorbers at \( 1.98 \leq z \leq 5.3 \). In contrast, the comoving \( dN/dz \) of weak Mg II systems with \( W_r(\lambda 2796) < 1 \) Å is nearly constant over cosmic time (Nestor et al. 2005; M12; Chen et al. 2017), which is quite different from that of strong systems.

In this paper, we present a sample of strong Mg II absorbers detected in the near-IR spectra of 31 quasars at \( z > 5.7 \) and study the evolution of their number density at \( 2.2 < z < 6.0 \). We also explore possible connections between the absorbers and properties of the associated galaxies. This paper is presented as follows. We introduce our sample and absorption detection method in Section 2. The results are presented in Section 3. We discuss possible galaxy counterparts in Section 4. Throughout the paper, all magnitudes are expressed in the AB system. The standard cosmology parameters are used: \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_m = 0.7 \) and \( \Omega_m = 0.3 \).

## 2. Data and Detection of Mg II Absorbers

The quasar near-IR spectra used in this paper were from a large Gemini-GNIRS program (Shen et al. 2019). Shen et al. observed most of the 52 quasars at \( z > 5.7 \) (Jiang et al. 2016) and this program was carried out during 15B-17A semester. By excluding those quasars that already have reasonable good quality spectra, the final sample consists of 50 quasars. Most of these 50 quasars were initially selected from Sloan Digital Sky Survey (SDSS) with a color cut of \( i - z > 2.2 \) and have no detection in \( ugr \) bands (Jiang et al. 2016). The observations were executed using the standard ABBA method. A cross-dispersion mode was used to cover the wavelength range from 0.85 to 2.5 \( \mu \)m. We use a slit width of 0.675 that delivers a resolving power \( R \sim 800 \) \((\sim 376 \) km s\(^{-1}\); GNIRS mean resolution) with a pixel scale of 0.15\("\)/pix. The spectral resolution is estimated from the average FWHM of weak and unblended emission lines in the arc file. The emission redshifts of quasars in the sample were measured from a series of lines \((\text{Mg II, C III}], \text{Si III}, \text{Al I III}], \text{C IV}, \text{He II, O I II}, \text{Si IV}, \text{Si IV})\), which takes the velocity shifts of each line into account (Shen et al. 2019). The updated redshifts may differ from the original redshifts in the discovery papers, which are with optical spectra only (see Table 1). The median emission redshift uncertainty is \( \sim 300 \) km s\(^{-1}\). The GNIRS data were reduced by the combination of two pipelines, PyRAF-based XDGNIRS (Mason et al. 2015) and the IDL-based XIDL package. The details are described in Shen et al. (2019).

We clarify that the quasar colors in our sample are consistent with that at lower redshift, hence, there is very limited bias caused by the background quasars for absorption candidates selection. Color bias of the background quasars in large samples would possibly affect the foreground absorbers selection. For example, in Prochaska et al. (2009), they found an elevated incidence of Lyman limit opacity in the intergalactic medium. This is related to the SDSS quasar selection bias at \( z = 3.5 \) to \( z = 3.6 \). Considering our sample size and quasar colors, this effect, if any, would be within errors and not affect significantly the absorption study results. Also, we did not select absorption candidates based on any presumptions of \( N (H I) \). The selection process of absorption candidates is presented in details in Section 2.1.

### 2.1. Detection Algorithm

We selected 31 quasars with signal-to-noise ratios \((S/N)\) greater than 10. The \( S/N \) is a mean \( S/N \) per resel measured from the “clean” continuum region of the spectra without strong OH skylines or water vapor absorption features. The mean \( S/N \) values of all spectra are presented in Table 1. Given the low resolution \((R \sim 800)\) of GNIRS spectra, we did not use the lower \( S/N \) spectra. We first fitted each quasar spectrum with a continuum. The continuum was selected interactively with knots in the absorption-free wavelength region. The region between two knots was fitted with a spline curve. Then the spectrum was normalized with this continuum. We then used our algorithm to automatically search and identify metal absorbers in the normalized spectra. The absorption feature was identified with a Gaussian kernel filter, which has a rest-frame velocity FWHM between 376 \( \) km s\(^{-1}\) and 600 km s\(^{-1}\) (six pixels, empirically selected). If \( W_r \) of this Gaussian kernel were greater than 0.8 Å, which is our detection limit (e.g., observe equivalent width \( \sim 3 \) Å around wavelength 10,000 Å) for Mg II line, then it was considered as an absorption feature. The \( W_r \) was measured from the flux summation over \( \Delta \lambda \) where the Gaussian kernel is within 3\% of the continuum. For Mg II doublet the two kernels of the doublet are separated by \( \sim 770 \) km s\(^{-1}\) and cross-correlated with the spectrum simultaneously. The selection criteria of Mg II candidates relate to \( W_r \), \( \sigma(W_r) \) and \( S/N \) in the continuum. We calculated the \( \sigma(W_r) \) by using a method by Vollmann & Eversberg (2006). For a normalized spectrum, the \( W_r \) of an absorption line is defined as:

\[
W_r = \int_{\lambda_2}^{\lambda_1} (1 - F) d\lambda \approx \Delta \lambda_r (1 - F),
\]

where \( \Delta \lambda_r = (\lambda_2 - \lambda_1)/(1 + z) \) is the rest-frame absorption line width. \( F \) is the mean normalized flux density of the absorption line. Equation (2) can be expanded in a Taylor series:

\[
W_r = W_r(F) + \frac{\partial W_r}{\partial F} \sigma(F).
\]

According to Equation (2), there is \( \frac{\partial W_r}{\partial F} = -\Delta \lambda. \) Together with

\[
\sigma(W_r) = \Delta \lambda \times \frac{F}{(S/N)_c}.
\]
The error of \( \Delta v \) was computed from the quadratic sum root of 1σ error of FWHM
\( \Delta \nu \), which are FWHMs of arc files and observed absorption profiles.

\( \Delta \nu \) returns the observed velocity width of Mg II \((\lambda 2796)\) lines. \( \Delta \nu \) Mean S/N of the spectra.

\( \Delta \nu \) is this Mg II doublet is strongly blended, so measurements have inevitable large uncertainties.

\( S/N \) is the average S/N per resol of ±10 pixels adjacent to \( \Delta \lambda \). The specific Mg II candidates selection criteria are in the following:

1. \( W_\lambda(\lambda 2796) / \sigma (W_\lambda) \) > 3.
2. \( W_\lambda(\lambda 2796) \) > 0.8 Å and \( W_\lambda(\lambda 2803) > 0.4 \) Å.
3. \( S/N \) > 3 per resol in three or more contiguous pixels beyond the \( \Delta \lambda \) region.

We searched for Mg II systems in all 31 quasar spectra using the above criteria and obtained 110 candidates.

Afterward, at least two Fe II lines (at 1608, 1611, 2344, 2374, 2586, or 2600 Å) were visually inspected at the same redshift to further confirm the identified Mg II doublet. In the end, we confirmed 32 Mg II and Fe II absorbers at \( 2.2 < z < 6.0 \). The spectra of the absorbers are presented in Figure 1. We found that all these Mg II absorbers have \( W_\lambda(\lambda 2796) > 1.0 \) Å, and 13 of them are very strong with \( W_\lambda(\lambda 2796) > 2.0 \) Å. The median \( W_\lambda \) is 1.86 Å. The redshift distribution (with a median \( z = 3.743 \)) of these absorbers is shown in Figure 2.
2.2. Measurements

We also measured \(W_r\) of an absorption candidate from a Voigt profile. The line is fitted using the VoigtFit package (Krogager 2018). During the visual inspection process, we noticed that our detection algorithm detected a few absorbers as candidates but they are strongly blended, e.g., Mg II (\(\lambda 2803\)) lines at \(z = 3.059\) (J0002+2550), \(z = 5.595\) (J0840+5624), \(z = 4.201\) (J1250+3130), and \(z = 4.530\) (J1335+3533). Due to this blending, the \(W_r\) would be overestimated from the flux boxcar summation. The Doppler parameter \(b\) values of the fits are between 20–60 km s\(^{-1}\). Because the relatively low resolution would introduce large uncertainties on the \(b\) and column density measurements, we only use Voigt fits to calculate the \(W_r\), which is independent of spectral resolution. We compared the measurements from the fits and the flux summation. Except for systems with obvious blending, the differences between the two measurements have a median of 0.13 Å and a maximum of 0.5 Å.

We then measured the velocity width from the best-fitted parameters. The intrinsic rest-frame velocity width \(\Delta v\) was...
The details are presented in the following and Table 2. This measurement is similar to the standard optical depth definition (Prochter et al. 2006). The idea is to include all satellite absorbers and to have a good representation of the kinematic extent of the absorption. We measured instrument broadening from lamp/arc lines used for wavelength calibration. The average FWHM of the arc lines FWHM_{arc} is roughly 376 ± 31 km s\(^{-1}\) (with 1σ error). The rest-frame intrinsic FWHM was calculated by FWHM = \sqrt{FWHM_{obs}^2 - FWHM_{arc}^2}/(1 + z), where FWHM_{obs} is the observed FWHM of the line. Then we assume the ratio of intrinsic FWHM and Δv_s is the same as the ratio of observed FWHM and Δv_{obs}, i.e., Δv = FWHM \times (Δv_{obs}/FWHM_{obs}).

To minimize the low resolution impact on our velocity spread measurements, we create 50 mock Mg II absorption spectra and convolved them into FIRE resolution of R = 6000 (i.e., 50 km s\(^{-1}\)) and GNIRS resolution of R ~ 800 (i.e., 376 km s\(^{-1}\)), respectively. Then we measured the Δv from the mock spectra with different resolutions using the same method described above. The measurements are consistent within errors ~20 km s\(^{-1}\) (see Figure 3). We also used a FIRE spectra of Fe II (λ2374) system at z = 3.495 toward QSO J0148+0702. We degraded the spectral resolution into R = 800. The velocity width measurement difference between the original and degraded spectra is within 30 km s\(^{-1}\).

The intrinsic and observed velocity widths of all the detected absorbers are shown in Table 1’s columns (7) and (8), respectively. We found that 15 out of 32 absorbers have Δv > 300 km s\(^{-1}\). We fit the relation between Δv and \(\lambda_p\) using a polynomial curve fitting technique considering the errors from two variables (see Figure 4).

\[ Δv = 75.63 \text{ km s}^{-1} \lambda^{-1} \times \lambda_p + 141.19 \text{ km s}^{-1}. \]

### 2.3. Comparison with C17

We compared measurements of five overlapping sightlines (J0203+0012, J0836+0054, J0842+1218, J1148+0702, and J2310+1855) between our sample and the FIRE sample in C17. The details are presented in the following and Table 2.

All Mg II systems in J0203+0012 and the one at z = 2.299 toward J0836+0054 reported in C17 are below 1 Å, which are beyond our detection limit. The \(\lambda_p\), Δv and z measurements of the system at z = 3.745 toward J0836+0054 are consistent. For J0841+1218, three systems were detected in this work and C17 at z = 5.050, 2.540, 2.392. The \(\lambda_p\), Δv and z measurements are consistent with errors. For J1148+0702, we detected two systems at z = 4.369 (\(W_\lambda(\lambda2796) = 4.23 \pm 0.52\) Å) and z = 3.495 (\(W_\lambda(\lambda2796) = 6.50 \pm 1.20\) Å). The measurements of the system at z = 4.369 are consistent with that in C17. The system at z = 3.495 has extremely large velocity width (>800 km s\(^{-1}\) for Mg II (λ2796) line) and the absorptions are strongly blended within the doublet. Thus, the \(\lambda_p\) and Δv measurements of this system inevitably have large uncertainties. We did not use this measurement when calculating the relation in Equation (5). For J2310+1855, the two systems at z = 3.299 and 2.351 detected in C17 have \(W_\lambda < 1.0\) Å, which are beyond our detection ability. The one at z = 2.243 is located in a noisy region where the lines are not able to be detected in our spectrum. We detected two systems at z = 4.244 and z = 4.013, which are not included in C17. The first one has \(W_\lambda(\lambda2796) = 1.86 \pm 0.35\) Å and Δv = 221 ± 34 km s\(^{-1}\). The second one has \(W_\lambda(\lambda2796) = 1.19 \pm 0.21\) Å and Δv < 165 km s\(^{-1}\) (see the last two panels in Figure 1). The system at z = 4.244 was present in an inspection of the spectrum used in C17, but was rejected by their automated search algorithm because \(W_\lambda(\lambda2803) > W_\lambda(\lambda2796)\), likely because of blending in the Mg II (λ2803) line from interloping systems at lower redshift. The system at z = 4.013 has severe telluric noise in FIRE spectrum (R. Simcoe 2020, private communication).

In summary, except for the systems where \(W_\lambda(\lambda2796) < 1\) Å or where the spectra S/N is too low, our absorption redshift, equivalent width and velocity spread measurements are consistent with that in C17, within errors. Though it is possible that, for systems where Δv_{obs} < 400 km s\(^{-1}\) (close to GNIRS resolution), our velocity widths uncertainties would be large.

### 3. Results

The near-IR spectra are strongly contaminated by OH skylines and telluric absorption. To conduct population
statistics analysis for absorbers, we need to correct the incompleteness caused by the contamination. In this section, we first correct these effects and then present the statistical $dN/dz$ and $dN/dX$ for our Mg II sample.

3.1. Completeness

For each quasar spectrum, we performed a Monte Carlo simulation by inserting uniformly distributed, virtual Mg II doublets in the wavelength range between 8500 Å and 20,000 Å, corresponding to the absorber redshifts of 2.0 and 6.2, respectively. The inserted $W_r(\lambda 2796)$ varies between 1.0 and 4.5 Å, which is the observed $W_r$ range of our detected Mg II absorbers (except for the strongly blended one toward J1148+0702). For each $W_r$, its velocity width follows the relation $\Delta v = 103.37 \text{ km s}^{-1} \frac{\text{Å}}{W_r} + 399.60 \text{ km s}^{-1}$, which we measured from the $\Delta v_{\text{obs}}$ and $W_r$. Two strong water vapor regions (1.35–1.42 μm between J and H and 1.82–1.93 μm between H and K band) are discarded in the statistical analysis of $dN/dz$ and $dN/dX$. Then we use the algorithm introduced in Section 2.1 to detect the inserted virtual absorbers. We measured the uncertainties between inserted and retrieved measurements from 1000 mock inserted Mg II systems. The measurement errors of $W_r$ and $z$ are 0.015 Å and 0.002, respectively (see Figure 5). This bias would be affect the final completeness significantly. The detection result is denoted as a Heaviside function $H(z, W_r)$:

$$H(z, W_r) = \begin{cases} 
1, & \text{if the absorber is detected,} \\
0, & \text{if the absorber is not detected.}
\end{cases}$$

The redshift-weighted density $g(z, W_r)$ is a function of $W_r$ and $z$ denoted as

$$g(z, W_r) = \sum_{i=1}^{N} H(z, W_r),$$

where $N$ is the total number of sightlines. The total path $g(z)$ is obtained as the integral of the path density over the whole...
range that we selected (see Figure 6):

\[
g(z) = \int_{W_0}^{\infty} g(z, W) \, dz,
\]

where \(W_0\) is the \(W_r\) limit. For each sightline, its completeness is the detection rate of the inserted absorbers. The completeness of pathlength is a function of redshift and \(W_r\):

\[
C(z, W_r) = g(z, W_r)/N.
\]

We show the pathlength-averaged completeness \(C(z, W_r)\) for the selected 31 sightlines with \(W_r(\lambda 2796) > 0.8\ \text{Å}, 1\ \text{Å}\) and >3 Å in Figure 7. For \(W_r(\lambda 2796) > 1\ \text{Å}\) the completeness is around 40% ~ 80% in the \(J\) band (1.17–1.37 \(\mu\)m), and around 20% ~ 60% in the \(H\) band (1.49–1.80 \(\mu\)m). The low completeness in the \(H\) band is due to the contamination of strong skylines.

Even if the \(S/N\) of a spectrum is high enough to detect weak lines, visual inspection may miss some weak absorbers. The probability for users to confirm true absorbers is defined as user acceptance. In M12 and C17, the user acceptance rate is defined as a function of \(S/N\) and has been considered in their calculations. M12 suggests that when \(S/N > 10\), the user acceptance is close to 1 and the rejection fraction of false-positive candidates is close to 0.

Zhu & Ménard (2013) identified 40,000 Mg II absorbers from SDSS at \(0.4 < z < 2.3\). By requiring the simultaneous detection of Fe II lines (\(\lambda\lambda 2344, 2383, 2586, 2600\)) for each Mg II absorption line, they recovered close to 100% of strong absorbers in the Pittsburgh catalogs (Quider et al. 2011). In this work, we focus on the strong system with \(W_r(\lambda 2796) > 1\ \text{Å}\), for which we also confirm detection of Fe II candidate lines at the same absorption redshift. Given this and that our database consists of spectra with \(S/N > 10\), we assume that our visual inspection is correct at a rate of ca 95%. In the case that one or two Fe II candidate lines reside in the water vapor region and are affected significantly by OH lines, the bias would be within this rate given the wide wavelength coverage of Fe II candidate lines. We calculated the Fe II lines association with strong Mg II systems in M12. We found that there are 35 out of 37 (94.5%) strong Mg II systems (\(W_r(\lambda 2796) > 1\ \text{Å}\)) associated with at least three clear Fe II lines. Additionally, spurious detection caused e.g., by C IV doublets \(W_r(\lambda 1548 > 0.5\ \text{Å})\), are not detected in our spectra. Therefore, the false-positive detection rate from the weaker lines is close to 0.
where \( N \) is the normalization and \( \beta \) is the slope. We apply the maximum likelihood estimation method to the relation and find that \( N_0 \) and \( \beta \) are 1.882 \( \pm \) 3.252 and \(-0.952 \pm 1.108\), respectively.

Previous studies (e.g., M12 and C17) have found that the \( dN/dz \) of strong Mg II absorbers generally decreases with increasing redshift at \( 2 < z < 6 \). In particular, the \( dN/dz \) or \( dN/d\Delta z \) at \( z > 4.5 \) drops rapidly (see Figure 8). Codoreanu et al. (2017) studied Mg II systems using four quasars from VLT-Xshooter and found that the \( dN/dz \) is relatively flat at \( 2 < z \leq 4 \). This is likely due to the larger uncertainties from their small sample, as they have pointed out in the paper. As shown in Figure 8, our results are consistent with the previous results within errors. The trend at \( 2 < z < 4 \) is not clear due to the large errors, but the density decreases significantly at \( z > 4.5 \).

### 3.3. Kinematics and Saturation

The evolution of Mg II incidence has implications for the origin of Mg II absorbers. One possible scenario is that superwinds give rise to strong Mg II absorbers in starburst galaxies (Bond et al. 2001; Heckman 2001; Bouché et al. 2006). Superwinds are gas bubbles generated by starbursts. They escape from gravitational wells and then blow into galaxy halos. Low-ions such as Mg II and Na I reside in the shells of these superwinds. Another possible scenario is that strong Mg II systems would reside in a galaxy groups environment. For example, Gauthier (2013) find their ultra-strong Mg II absorber \( (\lambda 2796) = 4.2 \) \( \AA \) at \( z = 0.5624 \) is associated with five galaxies within 60 kpc.

To further investigate the possible scenarios for the origin of our strong Mg II systems, we compare the velocity widths of our Mg II systems with those at similar and lower redshift. We compare with three samples in the literature: a blindly searched Mg II sample from SDSS DR12 (Zhu & Ménard 2013) at \( 0.4 < z < 2.3 \), Mg II systems associated with a DLA sample from the XQ-100 survey at \( 2 < z < 4 \) (Berg et al. 2017), and Mg II systems traced by a neutral atomic carbon (C I) sample at \( 1.5 < z < 2.7 \) (Zou et al. 2018). The comparison is plotted in Figure 9.

We found that the velocity widths of our Mg II absorbers are larger than those associated with DLAs with similar equivalent widths at \( 2 < z < 4 \), this feature is also seen in C17 strong Mg II systems. In the C17 sample of 287 absorbers, 104 of which have \( W_r(\lambda 2796) > 1 \) \( \AA \), and 58 out of 104 have \( \Delta v > 300 \) km s\(^{-1}\). Note that the \( \Delta v \) given in C17 is defined as the
Table 4
Photometry of Possible Galaxies Counterparts Around our Targets Selected

<table>
<thead>
<tr>
<th>Quasar</th>
<th>czabs</th>
<th>Targets NO.</th>
<th>R.A.</th>
<th>Decl.</th>
<th>F105W (mag)</th>
<th>M (mag)</th>
<th>D (kpc)</th>
<th>g (mag)</th>
<th>i (mag)</th>
<th>r (mag)</th>
<th>z (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0002+2550</td>
<td>3.059</td>
<td>1</td>
<td>00:02:39.24</td>
<td>+25:50:36.7</td>
<td>24.74 ± 0.08</td>
<td>−19.15 ± 0.08</td>
<td>20.2</td>
<td>&gt;25.78</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J0050+3445</td>
<td>3.435</td>
<td>1</td>
<td>00:50:06.99</td>
<td>+34:45:22.8</td>
<td>24.83 ± 0.08</td>
<td>−19.20 ± 0.08</td>
<td>29.7</td>
<td>25.44 ± 0.10</td>
<td>25.64 ± 0.11</td>
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<td>08:42:29.55</td>
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<td>24.72 ± 0.08</td>
<td>−19.72 ± 0.08</td>
<td>17.1</td>
<td>&gt;25.64</td>
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<td></td>
<td>24.72 ± 0.08</td>
<td>−18.94 ± 0.08</td>
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<td>24.72 ± 0.08</td>
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<td>+06:30:11.3</td>
<td>24.83 ± 0.12</td>
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<td>25.10 ± 0.16</td>
<td>−19.04 ± 0.12</td>
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<td>11.4</td>
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<td>+35:33:11.5</td>
<td>23.69 ± 0.04</td>
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<td>24.26 ± 0.05</td>
<td>−20.00 ± 0.05</td>
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<td>2.244</td>
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<td>25.10 ± 0.11</td>
<td>−19.15 ± 0.11</td>
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Note. The selection criteria is Δν > 300 km s\(^{-1}\) or \(W(\lambda 2796)\) > 1.5 Å. The 1 or 2 labels in the third column are galaxy candidates numbers in Figures 8 and 9. Two detection limit in g band for J0002+2550, J0842+1218, J1207+0630, and J1250+3130 are measured from public DECaLS imaging data. The g; r bands magnitudes for J0500+3445 and r; z bands magnitudes for J2310+1855 are measured from CFHT–MegaPrime.
total velocity interval under the continuum. Even if only 90% of their intervals are considered, half of the strong absorbers still have $\Delta v > 300$ km s$^{-1}$. In the DLA-tracing Mg II sample, 18 out of 29 Mg II absorbers have $W_r > 1$ Å but only one has velocity width greater than 300 km s$^{-1}$. Moreover, large velocity widths for Mg II absorbers are also seen in the C I-tracing Mg II absorbers at $1.5 < z < 2.7$. The velocity widths were measured by the same method described in Section 2.2. In the 17 systems of C I-tracing Mg II absorbers, 15 have $W_r > 1$ Å and 13 out of 15 (87%) have $\Delta v > 300$ km s$^{-1}$. C I has been shown to effectively trace molecular and cold gas at $z \sim 2$, and thus star formation activities. As discussed in Zou et al. (2018), the C I systems can be highly disturbed by superwinds or the interactions between several galaxies. Therefore, large velocity widths of our Mg II absorber suggest that our systems are potentially strongly affected by the galactic superwinds and/or the interaction within galaxy groups.

The two dashed lines in panel (b) are for $W_r(\lambda 2803)/W_r(\lambda 2796) = 1$ and 0.5, respectively. The ratio greater than one implies that Mg II doublets are strongly saturated. In our sample, about 42% of the absorbers have this line ratio greater than 0.8. This fraction is ~55% in the $0.4 < z < 2.3$ SDSS sample. Our Mg II systems are slightly less saturated than the absorbers at $z < 2.3$.

Another piece of possible supportive evidence is the equivalent width ratio of Fe II and Mg II lines ($W_r(\lambda 2600)/W_r(\lambda 2796)$). We compare our sample with the DLA-tracing Mg II sample at $2 < z < 4$ and a sample from Rodríguez Hidalgo et al. (2012) at low redshift. Rodríguez Hidalgo et al. (2012) analyzed 87 Mg II system with $W_r(\lambda 2796) > 0.3$ Å at $0.2 < z < 2.5$. They found that strong systems ($W_r(\lambda 2796) > 1$ Å) do not have small $W_r(\lambda 2600)/W_r(\lambda 2796)$ ratios in their sample. In panel (c) of Figure 9, our sample covers a wide range of the $W_r(\lambda 2600)/W_r(\lambda 2796)$ ratios. In particular, four systems among the strongest Mg II absorbers have smaller ratios ($W_r(\lambda 2600)/W_r(\lambda 2796) < 0.5$) than most of the other systems in the sample. The small $W_r(\lambda 2600)/W_r(\lambda 2796)$ values can be due to many reasons, e.g., kinematics evolution, dust depletion, and intrinsic [Mg/Fe] abundance in the gas phase. We here propose that the kinematic evolution of the profiles of the very strong absorbers is a possible reason. Which means, at high redshift, the number of unresolved subcomponents associated with strong Mg II absorbers may grow.

4. Discussion

Our strong Mg II systems exhibit large rest-frame velocity widths and potentially less saturation, the Mg II gas is potentially strongly affected by galactic superwinds or the interaction within galaxy groups. Previous studies suggest that both star-forming and passive galaxies may host Mg II absorbers. Star-forming galaxies tend to host stronger absorbers. Zibetti et al. (2007) studied 2,800 Mg II systems having $W_r(\lambda 2796) > 0.8$ Å at $0.37 < z < 1$ and associated galaxies within 20–100 kpc. They tentatively conclude that $W_r(\lambda 2796) < 1.1$ Å systems are associated with passive galaxies, while $W_r(\lambda 2796) > 1$ Å systems tend to be associated with star-forming galaxies. Lan et al. (2014) selected 2,000 galaxy-Mg II absorber pairs at $z < 0.5$ and found that, within 50 kpc, strong absorbers tend to be associated with star-forming galaxies. In this section, we will investigate the gas properties of the Mg II clouds, including gas cross-section, absorbing halo size, and the galaxy impact parameter.

4.1. HST Images

We have a small sample of HST snapshot images observed in the WFC3/IR F105W band (Program ID: 12184, PI: X. Fan). The images cover seven of our quasars with strong absorbers with $W_r(\lambda 2796) > 1.5$ Å or $\Delta v > 300$ km s$^{-1}$.
namely J0002+2550, J0050+3445, J0842+1218, J1207+0630, J1250+3130, J1335+3533, J1429+5447, and J1602+4228. Each figure size is $20'' \times 20''$, the yellow circle is in a $5''$ radius. The possible nearby galaxy are denoted as 1 or 2.

The rest-frame band of F105W at the median redshift of Mg II ($z = 3.743$) is $B$ band. The Lyman-Break Galaxies UV-continuum slope $\gamma (f_3 = \lambda^\gamma)$ measured by Bouwens et al. (2012) at $z \sim 4$ is around $-2$, therefore we have $u - b \sim 0$. If the galaxy is a passive galaxy, it is unable to be detected with present images. We then obtained $L_B/L_B^\ast = 0.25$, where $L_B$ and $L_B^\ast$ are the $B$ band luminosity of our galaxy candidates and $L^\ast$ galaxies, respectively. The result is consistent with the estimates of the Mg II associated galaxy luminosity in M12.

Because we only have a single photometric band measurement, we do not know their redshifts or whether they are associated with the detected absorption systems. We search the archival images of the Dark Energy Camera Legacy Survey (DECaLS; Dey et al. 2019) and find that four quasar fields are covered by DECaLS (J0002+2550, J0842+1218, J1207+0630, J1250+3130). None of the above galaxies are detected in the $grz$ bands. The $2\sigma$ detection limit in the $g$ band (the deepest band) is roughly 25.5 mag (see also Table 4). The red $g$–F105W color implies that these galaxies are likely at high redshift. We further estimate the surface density of $z > 2.5$ galaxies brighter than 25.5 mag in a few HST fields (Bouwens et al. 2015) and find that the expected number of random galaxies in a $5''$ circular area is about 0.1. This is significantly lower than our density of $>1$, suggesting that the galaxies detected in F105W above are likely associated with the strong absorbers. We can see that within 50 kpc of each absorber, we detected maximum two galaxy candidates. If multiple galaxies are associated with strong Mg II systems at high redshift, we need higher resolution spectra to disentangle the absorbing gas kinematic structure and deeper images to search for galaxy candidates nearby.

4.2. Gas Halo Size and Galaxy Impact Parameter

We have limited our search of galaxy candidates within a $5''$ (42.36 kpc at $z = 2.2$) radius, and we detected at least one candidate for each absorber within an impact parameter $D = 50$ kpc. This median distance of 23.31 kpc is smaller than the median distance, $\langle D \rangle = 48.7$ kpc found in the local universe (Schulze et al. 2012; Nielsen et al. 2013a, 2013b, 2018), suggesting that strong Mg II absorbers likely have smaller impact parameters at higher redshift. We can also calculate the absorbing halo gas size from the measured $dN/dz$ and $L_B/L_B^\ast$ using the relation from Kacprzak et al. (2008). The comoving line density ($dN/dz$) can be expressed as the product of the absorber physical cross-section $\sigma$ and volume comoving number density $n(z)$,

$$\frac{dN}{dz} = \frac{c}{H_0} \sigma n(z) \frac{dX}{dz},$$ (11)

where $c/H_0$ is the constant of proportionality and

$$\frac{dX}{dz} = \frac{(1 + z)^2}{\sqrt{\Omega_m(1 + z)^3 + \Omega_\Lambda}}.$$ (12)

The gas cross-section is expressed as $\sigma = \pi R_g^2$, where $R_g$ is the absorbing gas halo size. The volume number density $n(z)$ can
be expressed as a function of associated galaxy luminosity:

\[ n(z) = \Phi^* \times \Gamma(x, y), \]

where \( \Phi^* \) is the number density of \( L^* \) galaxies in the galaxy luminosity function. \( \Gamma(x, y) \) is an incomplete Gamma function with \( x = 2\beta - \alpha + 1 \), where \( \alpha \) is the faint-end slope of Schechter function and \( \beta \) is the factor of a relation between \( R_\alpha \) and associated galaxy luminosity (Steidel et al. 1995):

\[ R_\alpha = R_\alpha \times (L/L^*)^\beta. \]

\( y \) is the ratio of the detected galaxy minimum luminosity to \( L^* \). Therefore \( R_\alpha \) is:

\[ R_\alpha = \sqrt{\frac{dN/dX}{\pi \Phi^* \Gamma(x, y)}}. \]

We take \( \alpha = -1.64 \pm 0.04 \) from Bouwens et al. (2015), \( \beta = 0.35 \), our measured \( y = L_B/L_B^* = 0.25 \) and \( dN/dz \) at \( \langle z \rangle = 3.5 \), \( \Phi^*_B = 1.97^{+0.34}_{-0.28} \times 10^{-3} \text{ Mpc}^{-3} \) (Bouwens et al. 2015) to calculate the \( R_\alpha \). The \( \beta \) value is from Chen et al. (2010), which analyzed 47 \( \text{Mg II} \) associated galaxies at \( z < 0.5 \) and with \( 0.1 < W_r(\lambda 2796) < 2.34 \) \( \text{A} \). We assume the slope does not change at higher redshift. The \( R_\alpha \) is then estimated as follows:

\[ R_\alpha (\text{kpc}) = \begin{cases} 37, & \beta = 0.35, y = 0.05; \\ 8, & \beta = 0.35, y = 0.25. \end{cases} \]

With our measured \( L_B/L_B^* = 0.25 \), \( R_\alpha \) is smaller than the possible \( D \). This is based on the assumption that the covering fraction \( f_c \) of the gas is unity. The covering fraction of the absorbing gas is defined as the ratio of absorbers associated galaxies and all galaxies at the same redshift bin. Lan (2020) found that the covering fraction of strong \( \text{Mg II} \) systems evolves with redshift at \( 0 < z < 1.3 \), similarly to the evolution of SFR of galaxies. In the study of Chen et al. (2010), the \( \text{Mg II} \)-absorbing halo gas covering fraction is 70% for \( W_r(\lambda 2796) > 0.3 \) \( \text{A} \). Nielsen et al. (2018) studied 74 galaxies at \( 0.113 < z < 0.888 \) with \( \langle W_r(\lambda 2796) \rangle = 0.65 \) \( \text{A} \), and found \( f_c = 0.68 \) for isolated galaxies. Since we have 1–2 galaxy candidates within \( 5'' \) of the absorber, we adopt the \( f_c = 0.68 \). The covering fraction corrected size \( R_\alpha^* \) is 9.23 kpc \( (R_\alpha^* = f_c R_\alpha) \), which is still smaller than the \( (D) = 23.31 \) kpc.

In summary, we searched for associated galaxies around our strong \( \text{Mg II} \) absorbers at \( z = 3–5.1 \) within 50 kpc and found 1–2 candidates for each absorber. The galaxy candidates are brighter than 25.5 mag and have a median magnitude of 24.78 in \( \text{F105W} \) band. These candidates have a median impact parameter \( (D) = 23.31 \) kpc, which is smaller than that at \( z < 1 \). If we assume that the \( R_\alpha-L_s \) slope and \( f_c \) for strong \( \text{Mg II} \) absorbers at \( z = 3–5.1 \) are similar to that at \( z < 1 \), with a fixed associated galaxy luminosity \( L = 0.25L^* \) and a covering fraction of \( f_c = 0.68 \), the \( f_c \)-corrected absorbing halo gas \( R_\alpha \) is smaller than the \( (D) \). In other words, within 50 kpc, high redshift strong \( \text{Mg II} \) absorbers tend to have a more disturbed environment but smaller halo size than that at \( z < 1 \).

4.3. Individual Systems

In this subsection, we present a few individual systems with peculiar absorption features or having images in other bands. \( J0050+3445 \). We detected a \( \text{Mg II} \) absorber at \( z = 3.435 \) with \( W_r(\lambda 2796) = 3.44 \pm 0.88 \) \( \text{A} \). There are two galaxy candidates within \( 5'' \) from the quasar, labeled as 1 and 2 in Figure 10. We measure the \( g \) and \( r \) band magnitudes of the two objects using archived Canada–France–Hawaii Telescope (CFHT) MegaPrime images. The magnitudes of galaxy 1 are \( g = 25.44 \pm 0.10 \) and \( i = 25.64 \pm 0.11 \). The magnitudes of galaxy 2 are \( g = 25.43 \pm 0.10 \) and \( i = 24.89 \pm 0.13 \). The \( \text{Ly}_\alpha \) emission line at \( z = 3.435 \) is redshifted to 5391 \( \text{A} \) (g band), so galaxy 2 with \( g - i = 0.54 \) is more likely to be the absorber.

\( J2310+1855 \). We detected strong \( \text{Mg II} \) and \( \text{Fe II} \) at \( z = 4.244 \). In Figure 10 there are two galaxies within \( 5'' \) (25 kpc) from the quasar. The magnitudes of galaxy 1 are \( r = 25.55 \pm 0.14 \), \( z = 24.34 \pm 0.25 \), and \( F105W = 24.26 \pm 0.05 \). The magnitudes of galaxy 2 are \( r = 26.18 \pm 0.25 \) and \( F105W = 25.10 \pm 0.11 \). It is not detected in \( z \). Based on their colors, galaxy 1 is more likely to be the absorber host at \( z = 4.244 \). In addition, there is a bright object next to galaxy 1. But its \( m_s = 22.15 \) is much brighter than \( L^* \) at \( z \sim 4 \), so we did not consider it.
We detected Mg II and Fe II at z = 4.369 and z = 3.495, the latter one has extremely large velocity spread for a Mg II doublet. This one at z = 4.369 has a very strong Mg II (W_r(λ2796) > 4 Å) absorber with the strongest Fe II (W_r (λ2600) = 4.45 ± 0.82 Å) absorption in our sample. Both Mg II and Fe II lines are strongly saturated. As discussed in Joshi et al. (2017), strong Mg II and Fe II in the same system may indicate star formation nearby. We do not have HST images for this quasar. The Mg II and Fe II absorption profiles are presented in Figure 12.

5. Conclusion

We have analyzed the near-IR spectra of 31 luminous quasars at z > 5.7, selected from a sample of 50 quasars observed by Gemini GNIRS. We identified 32 Mg II and Fe II absorbers with Mg II W_r(2796) > 1.0 Å at 2 < z < 6.0. We calculated the line density dN/dz and comoving line density dN/dX of the strong Mg II absorbers and found that they decrease toward higher redshift at z > 3. This can be described by the relation dN/dz = (1.882 ± 3.252) × (1 + z)^{-0.952 ± 1.108}. The trend is consistent with previous results, and follows the evolution of the cosmic SFR, implying the correlation between strong Mg II absorbers with the star formation of galaxies at high redshift.

We found that 15/32 of our Mg II systems have large velocity widths with ∆v > 300 km s^{-1}, which is much larger than those detected in DLAs systems with similar equivalent widths at 2 < z < 4 and Mg II systems at z < 2. Such large velocity widths are also seen in a sample of neutral-carbon selected Mg II systems at 1.5 < z < 2.7. This potentially implies that strong Mg II systems at high redshift are influenced by galactic superwinds and/or interaction within galaxy groups. Also, our Mg II systems exhibit slightly less saturation in terms of the equivalent width ratio of Fe II and Mg II lines (W_r(2600)/W_r(2796)) ~ 0.5. This ratio is roughly between 0.25 and 1.75 in our sample. Our Mg II absorbers are possibly less saturated than DL–Mg II at 2 < z < 4 and those at z < 2.3 with similar equivalent widths. This is potentially caused by the interaction of more subcomponents of our strong Mg II systems.

We have used several HST images (together with archival DECaLS and CFHT images) to identify potential absorber galaxies within 50 kpc from quasars. For Mg II systems that have ∆v > 300 km s^{-1} or W_r(2796) > 1.5 Å, there are 1–2 galaxy candidates within the 5σ radius. The median F105W-band magnitudes is 24.83 mag, which is fainter than the galaxy luminosity relation at z > 3. This potentially implies that strong Mg II absorbers with the star formation of galaxies at high redshift.

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