Resolving the Internal Structure of Circumgalactic Medium Using Gravitationally Lensed Quasars

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Abstract

We study the internal structure of the circumgalactic medium (CGM), using 29 spectra of 13 gravitationally lensed quasars with image separation angles of a few arcseconds, which correspond to 100 pc to 10 kpc in physical distances. After separating metal absorption lines detected in the spectra into high ions with ionization parameter (IP) > 40 eV and low ions with IP < 20 eV, we find that (i) the fraction of absorption lines that are detected in only one of the lensed images is larger for low ions (~16%) than high ions (~2%), (ii) the fractional difference of equivalent widths (EWs) between the lensed images is almost the same (dEW ~ 0.2) for both groups although the low ions have a slightly larger variation, and (iii) weak low-ion absorbers tend to have larger dEW compared to weak high-ion absorbers. We construct simple models to reproduce these observed properties and investigate the distribution of physical quantities such as size and location of absorbers, using some free parameters. Our best models for absorbers with high ions and low ions suggest that (i) an overall size of the CGM is at least ~500 kpc, (ii) a size of spherical clumpy cloud is ~1 kpc or smaller, and (iii) only high-ion absorbers can have a diffusely distributed homogeneous component throughout the CGM. We infer that a high ionization absorber distributes almost homogeneously with a small-scale internal fluctuation, while a low ionization absorber consists of a large number of small-scale clouds in the diffusely distributed higher ionized region. This is the first result to investigate the internal small-scale structure of the CGM, based on the large number of gravitationally lensed quasar spectra.

Key words: galaxies: formation – intergalactic medium

1. Introduction

Cosmologically intervening metal absorbers detected in spectra of background quasars (e.g., Lanzetta & Bowen 1990; Bergeron & Boissé 1991) and galaxies (e.g., Adelberger et al. 2005; Steidel et al. 2010) are good probes of the circumgalactic medium (CGM) of foreground galaxies. The CGM, which is fuel for star formation in the galaxy and/or ejected matter blown out by galactic winds, recently attracts a lot of attention as it is a key ingredient to understand galaxy formation and evolution. Based on multiple galaxy-CGM spectroscopy, the radial gradient of equivalent width (EW) and column density (log N) of both hydrogen and metal absorbers in the CGM as a function of transverse and line-of-sight directions were built up to several proper Mpc (pMpc, hereafter) from galaxies at zabs < 0.5 (e.g., Chen et al. 2010a, 2010b; Prochaska et al. 2011; Tumlinson et al. 2011; Werk et al. 2016) and at zabs ~ 2–3 (e.g., Rakic et al. 2012, 2013; Turner et al. 2014, 2015; Rubin et al. 2015). Several studies have revealed the radial gradient of physical conditions in the CGM, such as covering factor (Cf), ionization parameter (log U), gas temperature (Tgas), and turbulence velocity (vTurb), e.g., Rakic et al. 2012; Rudie et al. 2012; Prochaska et al. 2013; Turner et al. 2014; Lau et al. 2016). Recently, projected 2D maps along our sight line have also been built through multi-line spectroscopy (Prochaska et al. 2014; Stern et al. 2016), deep narrowband imaging (Cantalupo et al. 2014; Hennawi et al. 2015), and integral field spectroscopy (e.g., Borissova et al. 2016). Arrigoni Battaia et al. (2016) suggested that diffuse Lyα emission from the CGM could distribute up to ~500 proper kpc (pkpc, hereafter) from quasar host galaxies with a detection limit of SBLyα = 5.5 × 10^-20 erg s^-1 cm^-2 arcsec^-2. Thus, a global picture of the CGM is being formed progressively.

On the other hand, very little has been known about an internal small-scale structure of the CGM, such as (i) their homogeneity or clumpiness, and (ii) a typical scale of each clumpy cloud (or density fluctuation) if the latter is the case. One of the difficulties in probing the CGM internal structure is that only one-dimensional distribution can basically be drawn using a background spectrum. Gravitationally lensed quasars are powerful tools for investigating an internal structure of the CGM. A typical separation angle of lensed images is a few to tens of arcseconds, corresponding to 100 pc to 100 kpc10 between two paths at z ~ 1–4 based on a

10 The largest separation distance corresponds to large-separation lensed quasars by a cluster of galaxies with a separation angle of θ > 10 arcsec.
standard cosmological model. These kinds of observations have already been partially performed for investigating cosmologically intervening absorbers (e.g., Smette et al. 1995; Monier et al. 1998). For example, based on spectra of the triply imaged quasar APM08279+5255, Ellison et al. (2004) suggested an important trend that H I absorbers and high ionization systems like C IV absorbers show coherence (i.e., coincidence) on the multiple sight lines over distances of \( \sim 100-300 \) kpc, while low ionization systems like Mg II exhibit significant sight line variation on scales greater than a few hundred parsecs. This is qualitatively consistent with a simple picture of clumpy, low ionization gas, embedded in homogeneous, highly ionized outer halos. These trends are also reminiscent of the hierarchical structure formation (e.g., Stern et al. 2016). However, sample sizes of the past studies (i.e., only a few lensed-quasars) are not large enough for statistical analysis.

In this paper, we collected a (large) sample of spectra of gravitationally lensed quasars to statistically study an internal structure of the CGM through comparisons of parameters, including absorption detection rate and rest-frame equivalent widths (REW) as a function of ionization condition and physical separation between lensed images. Because our goal is to resolve the internal small-scale structure of the CGM, we do not necessarily need to know the positions of the galaxies hosting the CGM giving rise to the absorption lines with respect to the background gravitationally lensed quasars. In Section 2, we describe the data sample and the methods used for detecting absorption lines and measuring their parameters. The results and discussion are presented in Sections 3 and 4, respectively. We summarize our results in Section 5. We use a cosmology with \( H_0 = 70 \text{ km s}^{-1}\text{ Mpc}^{-1} \), \( \Omega_m = 0.3 \), and \( \Omega_k = 0.7 \) throughout the paper.

### 2. Data and Analysis

We select our sample quasars from the Sloan Digital Sky Survey Quasar Lens Search (SQLS; Inada et al. 2012; Oguri et al. 2012 and reference therein). The SQLS repeatedly performed spectroscopic observations for gravitationally lensed quasar candidates with various telescopes and instruments, and discovered 62 lensed quasars. Because the quality of observed spectra (e.g., wavelength coverage, resolution, and signal-to-noise ratio (S/N) is heterogeneous, we select lensed quasars whose spectra satisfy all of the following criteria: (a) C IV and Mg II absorption lines are covered by optical spectra (i.e., quasar emission redshift is larger than 1.5), (b) spectral resolution is greater than 1000, (c) wavelength coverage is wide enough to cover from \( \sim 4000 \) Å to \( \sim 1 \mu m \), (d) data quality is high enough (i.e., an S/N is greater than \( \sim 20 \) pixel\(^{-1} \) on average after sampling in a spectrum). We use 20 spectra of 10 lensed quasars taken with Keck/ESI (wavelength resolution is \( \lambda / \Delta \lambda \sim 27,000 \)) or Gemini/GMOS (\( \lambda / \Delta \lambda \sim 1000 \)) from SQLS that satisfy the criteria described above (see Table 1).

Although the spectral resolution is very different between those taken with Keck/ESI and Gemini/GMOS, their pixel scale after sampling is almost the same, \( \sim 1.8 \) pix\(^{-1} \). We also confirmed the effect of self-blending (i.e., blue and red members of the doublet are blended with each other because of low spectral resolution) is not important when we measure EW later.\(^{11} \) We define the brighter quasar image as image 1 and the fainter as image 2 in optical bands. Parameters of absorption lines detected in each lensed image are shown with subscripts 1 or 2, hereafter.

In our spectra, we detect all absorption features (except for heavily blended ones) whose absorption depths at the center are greater than five times the noise level using the code SEARCH

\[ \text{Table 1} \]

| Lensed QSO | \( z_m \) | \( z_l \) | \( \theta \) (arcsec) | Instrument | \( \lambda \)-coverage (\( \lambda \)) | \( \lambda / \Delta \lambda \) | \( T_{\text{exp}} \) (s) | Reference
|-----------|------|-----|-------------------|------------|-----------------|-----------------|---------|--------
| SDSS J024634.11-z082536.2 | 1.686 | 0.724 | 1.04 | Keck/ESI | 3900–11000 | \( \sim 27000 \) | 900 | 1
| SDSS J074653.03+z044351.3 | 1.998 | 0.513 | 1.08 | Keck/ESI | 3900–11000 | \( \sim 27000 \) | 1200 | 2
| SDSS J080623.70+z020631.9 | 1.538 | 0.573 | 1.49 | Keck/ESI | 3900–11000 | \( \sim 27000 \) | 900 | 3
| SDSS J100040.15+151254.5 | 1.826 | 0.30 | 1.13 | Gemini/GMOS | 3700–9800 | \( \sim 1000 \) | 4200 | 4
| SDSS J092455.87+z021924.9 | 1.523 | 0.394 | 1.81 | Keck/ESI | 3900–11000 | \( \sim 27000 \) | 1200 | 5
| SDSS J110126.61+052756.8 | 1.841 | 0.415 | 2.86 | Gemini/GMOS | 3700–9800 | \( \sim 1000 \) | 4800 | 6
| SDSS J113157.72+191527.7 | 2.915 | 0.30 | 1.46 | Gemini/GMOS | 3700–9800 | \( \sim 1000 \) | 4800 | 4
| SDSS J125819.24+165717.6 | 2.702 | 0.505 | 1.28 | Gemini/GMOS | 3700–9800 | \( \sim 1000 \) | 4800 | 7
| SDSS J134929.84+122706.8 | 1.722 | 0.65 | 3.00 | Gemini/GMOS | 3700–9800 | \( \sim 1000 \) | 3600 | 4
| SDSS J135306.35+113804.7 | 1.624 | 0.25 | 1.41 | Keck/ESI | 3900–11000 | \( \sim 27000 \) | 600 | 3
| HE1104–1805 | 2.319 | 0.73 | 3.19 | 3.9 m-AAT/RGO | 3170–7570 | \( \sim 12000 \) | \( \sim 5200 \) | 8
| H1413+1143 | 2.551 | 1.88 | 0.76, 0.86, 1.10 | HST/FOG | 3250–6500 | \( \sim 1500 \) | \( \sim 4600 \) | 9
| APM08279+5255 | 3.911 | 1.06 | 0.15, 0.38 | HST/STIS | 5970–8600 | \( \sim 5000 \) | \( \sim 14000 \) | 10

**Notes.**

\( ^a \) Quasar emission redshift.

\( ^b \) Redshift of a foreground lensing galaxy. Approximate values are photometric redshifts rather than spectroscopic redshifts.

\( ^c \) Separation angle between lensed images seen from us in arcseconds.

\( ^d \) Redshift of a foreground lensing galaxy. Approximate values are photometric redshifts rather than spectroscopic redshifts.

\( ^e \) Spectral resolution.

\( ^f \) References: (1) Inada et al. (2005); (2) Inada et al. (2007); (3) Inada et al. (2006); (4) Kayo et al. (2010); (5) Inada et al. (2003); (6) Oguri et al. (2005); (7) Inada et al. (2009); (8) Smette et al. (1995); (9) Monier et al. (1998); (10) Ellison et al. (2004).
(Churchill 1997; Churchill et al. 2003). Then, we identify double lines such as C IV, Si IV, and Mg II in the spectral region between Lyα and the corresponding emission lines. We also search for other single metal lines at the same redshift as the double lines above.

For all detected doublets, we measure absorption redshifts (z1, z2) and rest-frame EWs (REW1, REW2) with their 1σ uncertainties (σ(REW1), σ(REW2))\(^{12}\), in the spectra of both blended images. Because blue and red members of the doublet are sometimes blended with each other, especially for the low-resolution spectra taken with Gemini/GMOS, we calculate the total REWs of two transitions, C IV λλ 1548, 1551 (C IV 1550, hereafter) and Mg II λλ 2796, 2803 (Mg II 2800, hereafter), including both doublet members. We chose C IV and Mg II doublets as representative transitions for high- and low ionization transitions because these doublets are most frequently detected among each category. We also measure the above parameters for the other metal lines.

We also calculate the physical separation in the transverse direction (D\(_{\text{trans}}\))\(^{13}\) and the fractional EW difference (Ellison et al. 2004) defined by

\[
\text{dEW} = \frac{|\text{REW}_1 - \text{REW}_2|}{\max(\text{REW}_1, \text{REW}_2)}. \tag{1}
\]

Because absorption strength is enhanced (compared to the intergalactic medium) around galaxies up to Δv ∼ 240 km s\(^{-1}\) along the line of sight for H I and metal absorption lines including C IV (Turner et al. 2014), we assume absorption lines within 400 km s\(^{-1}\) (i.e., ≲240 × 2 km s\(^{-1}\)) of each other are part of a single absorption “system.” As a result, we detected 30 C IV, 8 Si IV, and 39 Mg II doublets as well as 46 single metal lines in 36 absorption systems in total (see Table 2).

In addition to our data, we also include similar measurements from the literature for our statistical analysis: double images of HE1104−1805 (a quasar emission redshift is z\(_{\text{em}}\) = 2.319, a redshift of the lensing galaxy is z\(_{1}\) = 0.73, and a separation angle is θ = 3\(^{\circ}\)19) taken with 3.9 m-AAT/RGO (λ/Δλ ∼ 12,000, λ = 3200−7500 Å; Smette et al. 1995), quartet images of H1413+1143 (z\(_{\text{em}}\) = 2.551, z\(_{1}\) = 1.88, θ = 1\(^{\circ}\)10) taken with HST/FOS (λ/Δλ ∼ 1300, λ = 3200−6500 Å; Monier et al. 1998), and triple images of APM08279+5255 (z\(_{\text{em}}\) = 3.911, z\(_{1}\) = 1.062, θ = 0\(^{\circ}\)538) taken with HST/STIS (λ/Δλ ∼ 5000, λ = 6000−8600 Å; Ellison et al. 2004), as shown in Table 1.

To avoid any possible biases for statistical analysis, we accept only absorption lines that satisfy all of the following criteria: (a) they are blueshifted more than 5000 km s\(^{-1}\) from quasar emission redshifts to avoid contamination by absorption lines that are physically associated with the background quasars, (b) they have line widths smaller than the criterion for broad absorption lines (i.e., 2000 km s\(^{-1}\)) for the same reason as that mentioned above, (c) they are not heavily blended with other unrelated absorption lines, (d) their EW is larger than three times the noise level (i.e., REW \(\geq 3\sigma\)(REW))

\(^{12}\) This is defined by σ(REW) = \(\sqrt{\sum_{i=1}^{N} I_i \sigma_i^2}\), where N is a number of pixels in the absorption profile, I is the error in the normalized flux at pixel i, and Δλ is the width of each pixel in angstrom.

\(^{13}\) The separation distance between lensed images in the transverse direction is calculated by D\(_{\text{trans}}\) = θ\(_{\text{arc}}\) if z\(_{\text{abs}}\) < z\(_{1}\) and D\(_{\text{trans}}\) = θ\(_{\text{arc}}\) sin(θ\(_{\text{arc}}\)) if z\(_{\text{abs}}\) > z\(_{1}\), where θ\(_{\text{arc}}\) is an angular separation of the lensed images seen from us, and the subscripts o, s, i, and q for D (an angular diameter distance) and z denote observer, absorber, lensing galaxy, and quasar, respectively. We use an average value of z\(_{1}\) and z\(_{2}\) for z\(_{\text{abs}}\).

\(^{14}\) This is a significance level in absorption strength (i.e., EW), while we detected all of the above absorption lines (regardless of absorption strength) based on their absorption depth (>5σ) at the line center.

3. Results

We classify all absorption lines into two groups; two-on (2on) and one-on (1on) samples based on line detection with the \(\geq 3\sigma\) (σ(REW)) level in both or one of two spectra of lensed images within 400 km s\(^{-1}\) from each other. We also divide absorption lines into three classes based on their ionization potential (IP): high ions with IP > 40 eV (e.g., N v, C IV, and Si v), low ions with IP < 20 eV (e.g., Al II, Ni II, Si II, Fe II, Mn II, Mg II, N I, O I, Ca II, and Mg I), and intermediate ones (20 eV \(\leq\) IP \(\leq\) 40 eV; e.g., Si III, Al III, and C II). As a result, we separate 63 high ions into 59 two-on and 4 one-on samples, and 99 low ions into 72 two-on and 27 one-on samples, respectively. The rest of them are absorption lines of intermediated ionized ions. All high/low-ionized absorption lines within 400 km s\(^{-1}\) are grouped into the “single” absorption system, but most of them have velocity distributions smaller than 100 km s\(^{-1}\).

Figure 1 shows distributions of the physical distance in the transverse direction (D\(_{\text{trans}}\)) between the sight lines for high-ion and low-ion ionization absorbers as a function of absorption redshift. The thick black curve denotes a physical distance between the sight lines corresponding to the typical lensed quasar from SQLS (z\(_{\text{em}}\) = 2.3, z\(_{1}\) = 0.5, and θ = 2\(^{\circ}\)0). For high ions, our Gemini/GMOS and Keck/ESI spectra sample absorbers with D\(_{\text{trans}}\) \(\sim\) 0.1–1 kpc at z\(_{\text{abs}}\) \(\sim\) 1.5–2.5. Ellison et al. (2004) sample absorbers at higher redshift up to z\(_{\text{abs}}\) \(\sim\) 3.6, while Monier et al. (1998) and Smette et al. (1995) sample those with larger physical distance up to D\(_{\text{trans}}\) \(\sim\) 10 kpc. On the other hand, for low ions all data source sample absorbers with D\(_{\text{trans}}\) \(\sim\) 0.1–10 kpc at z\(_{\text{abs}}\) \(\sim\) 0.5–2.0, although Ellison et al. (2004) have several samples at higher redshift up to z\(_{\text{abs}}\) \(\sim\) 3. By combining our high-ion samples (black and red open circles in Figure 1) with that of Ellison et al. (2004; blue open circles in Figure 1), we can examine the redshift evolution of absorbers with a scale of D\(_{\text{trans}}\) \(\sim\) 0.1–1 kpc. On the other hand, we can examine physical properties of absorbers with a wide range of distance in D\(_{\text{trans}}\) \(\sim\) 0.1–10 kpc at z\(_{\text{abs}}\) \(\sim\) 2.

We first compare strengths of absorption lines (i.e., EW) in the two sight lines as shown in Figure 2 for high and low ions. Samples from Ellison et al. (2004) and Smette et al. (1995) tend
| Lensed QSO | Ion | \( \bar{z} \) | \( \sigma(\text{REW}) \) (Å) | \( \bar{z}_2 \) | \( \sigma(\text{REW}) \) (Å) | \( D_{\text{LS}} \) (pkpc) | \( \text{dEW} \) | \( \sigma(\text{dEW}) \) |
|-----------|-----|--------|-----------------|--------|-----------------|-----------------|--------|-----------------|
| SDSS J024634.11−082536.2 | Mg II 2800 | 0.7246 | 0.692 | 0.041 | 0.7256 | 0.978 | 0.068 | 7.86 | 0.292 | 0.064 |
| SDSS J074653.03+440351.3 | Mg II 2800 | 1.6505 | 0.442 | 0.036 | \(<0.116\) | 0.642 | \(>0.738\) | ... |
| SDSS J080623.70+200631.9 | Fe II 2600 | 0.5736 | 1.530 | 0.123 | 0.5743 | 2.291 | 0.271 | 9.729 | 0.332 | 0.095 |
| SDSS J090404.15+151254.5 | Mg II 2800 | ... | \(<0.158\) | ... | \(<0.157\) | ... | \(<0.157\) | ... | \(<0.157\) | ... |
| SDSS J100128.61+502756.8 | Fe II 2600 | 1.2169 | 0.964 | 0.035 | 1.2170 | 0.557 | 0.065 | 0.886 | 0.422 | 0.071 |
| SDSS J113157.72+191527.7 | Mg II 2800 | 1.1782 | 1.284 | 0.213 | 1.1799 | 0.536 | 0.076 | 0.276 | 0.404 | 0.086 |
| SDSS J125819.24+165717.6 | C IV 1550 | 1.1847 | 1.361 | 0.058 | 1.1857 | 1.298 | 0.066 | 1.103 | 0.047 | 0.063 |
| SDSS J134929.84+122706.8 | Mg II 2800 | 0.4913 | 0.936 | 0.083 | \(<0.622\) | 18.141 | \(>0.336\) | ... |

| Lensed QSO | Ion | \( \bar{z} \) | \( \sigma(\text{REW}) \) (Å) | \( \bar{z}_2 \) | \( \sigma(\text{REW}) \) (Å) | \( D_{\text{LS}} \) (pkpc) | \( \text{dEW} \) | \( \sigma(\text{dEW}) \) |
|-----------|-----|--------|-----------------|--------|-----------------|-----------------|--------|-----------------|
| C IV 1550 | 1.8474 | 1.361 | 0.058 | 1.8475 | 1.298 | 0.066 | 1.103 | 0.047 | 0.063 |
| Si IV 1393 | 1.9957 | 1.096 | 0.086 | 1.9960 | 1.112 | 0.090 | 0.837 | 0.015 | 0.111 |
| C IV 1550 | 1.9973 | 1.159 | 0.053 | 1.9989 | 1.374 | 0.064 | 0.833 | 0.156 | 0.055 |
| C IV 1550 | 2.1062 | 1.019 | 0.047 | 2.1066 | 0.855 | 0.056 | 0.664 | 0.161 | 0.067 |
| Si IV 1393 | 2.2301 | 0.198 | 0.028 | 2.2305 | 0.147 | 0.024 | 0.466 | 0.259 | 0.158 |
| C IV 1550 | 2.2500 | 0.555 | 0.092 | 2.2504 | 0.358 | 0.110 | 0.466 | 0.355 | 0.224 |
| Si IV 1393 | 2.3868 | 0.631 | 0.045 | 2.3865 | 0.813 | 0.064 | 0.304 | 0.223 | 0.082 |
| C IV 1550 | 2.3848 | 0.521 | 0.066 | 2.3852 | 0.783 | 0.078 | 0.305 | 0.335 | 0.107 |
| Al II 1670 | 2.3842 | 0.344 | 0.036 | 2.3846 | 0.407 | 0.036 | 0.306 | 0.154 | 0.116 |
| Fe II 2600 | 2.3840 | 0.428 | 0.036 | 2.3843 | 0.472 | 0.037 | 0.306 | 0.093 | 0.104 |
to have smaller REWs, while those from Monier et al. (1998) and our sample have larger values. This is because the former are detected in spectra with higher S/Ns (i.e., due to a technical reason). Correlation coefficients between REWs along sightline pairs are almost the same; \( r = 0.981 \) and \( r = 0.933 \) for high ions and low ions, respectively (see Figures 2(a) and (c)). However, we find larger scatter for low ions (\( r = 0.594 \)) compared to high ions (\( r = 0.941 \)) if we consider only weak absorption lines with \( \text{REW} > 2 \) Å as noted in Ellison et al. (2004); see Figures 2(b) and (d). This could be due to a clustering effect. If strong/weak absorption lines correspond to regions with high/low number density of gas clouds, only the weaker ones with a sparse cloud distribution are affected by a typical scale of each cloud that should be smaller for low-ionized absorbers.

Thus, a typical scale of absorbers probably depends on their ionization condition; those in the higher ionization condition tend to have larger sizes (e.g., Stern et al. 2016). Therefore, we investigate the fractional EW difference \( \text{dEW} \) as a function of transverse distance between sight lines as shown in Figure 3. Because most absorption systems in our sample are detected at redshifts higher than those of lensing galaxies (i.e., \( z_{\text{abs}} > z_{\text{q}} \)), the corresponding physical separation between sight lines becomes larger at lower redshift. Therefore, low ions, such as Mg II and Fe II, whose rest-frame wavelengths are larger than those of high ions like C IV and Si IV, are detected at lower redshifts and we can perform multiple sight line spectroscopy only for larger separation distances.

We then compare the \( \text{dEW} \) distributions as a function of \( D_{\text{tra}} \) after separating \( D_{\text{tra}} \) into three bins for high- and low-ion samples in such a way that each bin contains almost the same number of absorption lines. Because we confirmed that the \( \text{dEW} \) distribution is not Gaussian, we regard the range between 30% and 70% of the \( \text{dEW} \) distribution in each bin as a core distribution range of \( \text{dEW} \) (\( \text{dEW} \) box, hereafter; see Figure 3). The \( \text{dEW} \) box for high ions are \( 0.10–0.20 \), \( 0.10–0.26 \), and \( 0.08–0.17 \) in \( D_{\text{tra}} \) of \( 0.02–0.2 \), \( 0.2–2.0 \), and \( 2.0–10.0 \) kpc, while the \( \text{dEW} \) box for low ions are \( 0.13–0.42 \), \( 0.07–0.33 \), and \( 0.17–0.42 \) in \( D_{\text{tra}} \) of \( 0.1–1.0 \), \( 1.0–3.0 \), and \( 3.0–20.0 \) kpc, respectively. We confirm that the \( \text{dEW} \) distributions are almost independent of \( D_{\text{tra}} \) for both the high- and low-ion samples (\( \text{dEW} \sim 0.2 \)) although the low-ion sample has a slightly larger variation. We also do not find any remarkable redshift evolution of the \( \text{dEW} \) distribution for high-ion absorbers in the range of \( D_{\text{tra}} \sim 0.1–1 \) kpc, comparing our sample at \( z_{\text{abs}} \sim 2 \) (black and red filled circles in Figure 3) and those from Ellison et al. (2004) at \( z_{\text{abs}} \sim 3.3 \) (blue filled circles in Figure 3).

We also compare the fraction of one-on lines (one-on ratio, hereafter) defined by

\[
R_{\text{ion}} = \frac{N_{\text{ion}}}{N_{\text{on}} + N_{\text{ion}}},
\]

where \( N_{\text{ion}} \) and \( N_{\text{on}} \) are numbers of one-on and two-on lines. Because the \( R_{\text{ion}} \) value strongly depends on the quality of spectra (i.e., detection limit), we calculate the ratio using only reliable one-on lines; \( 3 \sigma \) detection limit on \( \text{REW} \) in an undetected sight line is smaller than 50% of \( \text{REW} \) in a detected

### Table 2
(Continued)

| Lensed QSO | Ion | \( z_{\text{i}} \) | \( \text{REW}_1 \) \((\text{Å})\) | \( \sigma(\text{REW}_1) \) \((\text{Å})\) | \( z_{\text{q}} \) | \( \text{REW}_2 \) \((\text{Å})\) | \( \sigma(\text{REW}_2) \) \((\text{Å})\) | \( D_{\text{tra}} \) \((\text{pkpc})\) | \( \text{dEW} \) | \( \sigma(\text{dEW}) \) |
|------------|-----|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Fe II 2600 | 1.2374 | 1.559 | 0.052 | 1.2376 | 1.974 | 0.070 | 5.812 | 0.210 | 0.052 |
| Mg II 2800 | 1.2373 | 3.838 | 0.035 | 1.2375 | 4.456 | 0.071 | 5.814 | 0.241 | 0.014 |
| Mg I 2853 | 1.2373 | 0.546 | 0.027 | 1.2375 | 0.817 | 0.058 | 5.814 | 0.332 | 0.058 |
| SDSS J135306.35+113804.7 | | | | | | | | | | |
| Mg II 2800 | 0.6377 | 1.032 | 0.052 | 0.6378 | 0.982 | 0.025 | 2.663 | 0.049 | 0.058 |
| Fe II 2600 | 0.9047 | 0.773 | 0.022 | 0.9048 | 1.263 | 0.009 | 1.537 | 0.387 | 0.018 |
| Mg II 2800 | 0.9047 | 2.300 | 0.033 | 0.9048 | 3.460 | 0.017 | 1.537 | 0.335 | 0.010 |
| Mg I 2853 | 0.9045 | 0.317 | 0.015 | 0.9048 | 0.292 | 0.045 | 1.538 | 0.080 | 0.149 |
| Fe II 2600 | 1.2386 | 0.204 | 0.022 | 1.2389 | 0.103 | 0.012 | 0.636 | 0.493 | 0.079 |
| Mg II 2800 | 1.2387 | 0.983 | 0.026 | 1.2385 | 0.941 | 0.017 | 0.636 | 0.042 | 0.031 |
| C IV 1550 | | \(<0.534\) | \(\ldots\) | 1.5689 | 0.978 | 0.062 | 0.073 | \(>0.454\) | \(\ldots\) |

**Notes.**

a Absorption redshift is larger than the quasar emission redshift.

b Broad absorption line (BAL) with an FWHM \( \geq 2000 \text{ km s}^{-1} \).

c Velocity shift from the quasar emission redshift is smaller than 5000 \text{ km s}^{-1} .

d This line is blended with other physically unrelated lines.

**Figure 1.** Physical distance between sight lines of lensed images (\( D_{\text{tra}} \)) as a function of absorption redshift (\( z_{\text{abs}} \)). Data from our sample are shown with black (Gemini/GMOS) and red (Keck/ESI), while those from the literature are shown with blue (Ellison et al. 2004), green (Monier et al. 1998), and purple (Smette et al. 1995). Open circles and crosses denote high-ion and low-ion absorption lines, respectively. Strong absorption lines with \( \text{REW} > 2 \) Å are also included in the figure. The thick black curve denotes a physical distance between the sight lines, corresponding to the typical lensed quasar from SQLS (\( \zeta_{\text{q}} = 2.3, \ z_{\text{i}} = 0.5, \ \text{and} \ \theta = 2\sigma(\text{REW}) \).
sight line (i.e., $6\sigma(\text{REW}_{\text{undet}}) < \text{REW}_{\text{det}}$)\(^{15}\) to find larger values for low ions ($R_{\text{ion}} \sim 0.16$) than high ions ($R_{\text{ion}} \sim 0.02$). This result suggests that a typical scale of low-ion absorbers is smaller than those of high-ion absorbers, which is consistent with the results from past studies (e.g., Ellison et al. 2004; Stern et al. 2016) and the correlation analysis for weak absorption lines (Figures 2(b) and (d)).

\(^{15}\)REW\(_{\text{det}}\) is a rest-frame EW in spectra of detected sight lines, while $\sigma(\text{REW}_{\text{undet}})$ is a 1σ detection limit on EW in spectra of undetected sight lines.

4. Discussion

In the previous section, we discovered several properties on dEW and $R_{\text{ion}}$ for high and low-ion absorbers. In order to connect our findings with the internal structure of the CGM that cannot directly be observed, we construct simple models to reproduce the observed properties. We assume a two-component model for the CGM: a number of spherical gas clouds are embedded in diffusely distributed gas and both of them give rise to the metal absorption lines. Although the ionization state depends on several parameters, including electron density, photon density, and gas temperature, we
distributions as a function of growth. We can apply this assumption to a substantial fraction of our samples. If absorption lines are not saturated with upward arrows. The range of 30%–70% of the dEW box and one-on ratio (R_{ion}) are shown with orange rectangles and open diamonds after separating the D_{los} range into three bins.

Among several free parameters, we first consider physical acceptable functions for the radial distribution of the EW. In this paper, we assume three simple EW(r) functions described below.

(a) **Elliptical function:** If absorbers have a spherical shape with no internal structure (i.e., homogeneous density), an EW is proportional to a projected depth of the absorber unless an absorbing cloud is optically thick. In this case, the EW distribution is expressed by

\[
EW(r) = EW_{\text{max}} \sqrt{1 - \frac{r^2}{(d/2)^2}},
\]

where \( r \) is the distance from the center of each spherical cloud, \( d \) is a diameter of the cloud, and \( EW_{\text{max}} \) is an intensity of EW at \( r = 0 \).

(b) **Inverse proportional function:** Another possible model is a singular isothermal sphere with the radial density distribution of \( \rho(r) \propto r^{-2} \). In this model, a projected density (i.e., column density) at a distance from the center \( r \) is approximately expressed by an inverse proportional function, except at a very large radius. To avoid it from diverging to infinity at the center, we slightly change the function into

\[
EW(r) = EW_{\text{max}} \left( \frac{d}{EW_{\text{min}} - EW_{\text{min}}^2} \right) \left( r + \frac{d}{EW_{\text{max}} - EW_{\text{min}}^2} \right).
\]

where \( EW_{\text{min}} \) is the minimum observational value of EW in our sample.

(c) **Linear function:** For comparison to the results from models adopting the above EW distributions, we also examine a simple model expressed by

\[
EW(r) = \frac{EW_{\text{max}}}{(d/2)} + EW_{\text{min}}.
\]

We adopt a dimensionless number to set \( EW_{\text{max}} = 1 \) as the maximum EW at the center, because we only measure the fractional EW difference (dEW) (i.e., the amplitudes of \( EW_{\text{max}} \) and \( EW_{\text{min}} \) themselves do not necessarily have to be measured). We also regard sight lines with EWs greater than \( EW_{\min} = 0.01 \) as absorption-detected sight lines because the ratio of the maximum and the minimum EWs in our observed sample is \(~100\). The radial distribution functions for an EW depend mainly on the dEW distribution as a function of D_{los}. As shown in Figure 5(a), the elliptical and the inverse proportional functions show almost the same patterns of dEW and R_{ion} distributions as a

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Fractional equivalent width (dEW) and one-on ratio (R_{ion}) for high (top) and low (bottom) ions as a function of sight-line separation (D_{los}). The meanings of symbol colors are the same as those in Figures 1 and 2. If absorption lines are of the one-on sample, only lower limits of dEW are plotted with upward arrows. The range of 30%–70% of the dEW distribution (dEW box) and one-on ratio (R_{ion}) are shown with orange rectangles and open diamonds after separating the D_{los} range into three bins.}
\end{figure}
function of $D_{\text{vir}}$, which match to the observed trends well (i.e., the dEW box is ~0.2 and almost independent of $D_{\text{vir}}$), although $R_{\text{ion}}$ is rather overestimated. Among the two acceptable functions, we will use the elliptical function as our default model. As for the other parameters, we use $d = 1$ kpc, $L = 50$ kpc, and $C_1 = 1$ with no diffusely distributed homogeneous gas (EW$_{\text{diff}} = 0$) as default parameters.

Next, we consider models with different sizes of each spherical cloud, $d = 0.5$, 1, 5, and 10 kpc using default values for all of the other parameters. It is clear that both dEW and $R_{\text{ion}}$ start to rise at smaller $D_{\text{vir}}$ for models with smaller cloud sizes (see Figure 5(b)). We also change an overall size $L$ from 50, 100, to 500 kpc. As shown in Figure 5(c), any clear differences are not seen in the dEW distribution. On the other hand, $R_{\text{ion}}$ tends to have larger values at $D_{\text{vir}} \geq 1$ kpc, especially for models with smaller overall size. This is because a number of one-on pairs that locate at the edge of overall area increase for those models.

In addition to the clumpy spherical gas clouds, the CGM could have a diffusely distributed homogeneous gas whose ionization condition is higher than that of the spherical clouds because of lower gas density. We add such a component (we call this diffuse gas, hereafter) whose EW is 10% of the central value (i.e., EW$_{\text{diff}} = 0.1$) throughout the overall area. Once the diffuse gas is added, one-on pairs are seen only at the edge of the overall area, which decreases $R_{\text{ion}}$ significantly as shown in Figure 5(d). We also consider models with four diffuse gas intensities with EW$_{\text{diff}} = 0.01$, 0.05, 0.1, and 0.5 for the elliptical function and EW$_{\text{diff}} = 0.01$, 0.02, and 0.05 for the inverse proportional function. Although both functions have acceptable models, their diffuse gas intensities are very different; the best models have diffuse gas intensity of EW$_{\text{diff}} = 0.5$ and 0.01 for the elliptical and the inverse proportional functions, respectively (Figures 5(e) and (f)).

Lastly, we consider the covering factor $C_r$, which is the fraction of the overall area that is covered by a number of spherical clouds, in Figure 5(g). Here, we regard $C_r = 1$ if clumpy clouds are regularly arranged with no gaps between clouds, although there are cracks in the diagonal directions (see Figure 4). If we decrease the covering factor down to 0.5, $R_{\text{ion}}$ increases significantly to become inconsistent with the observation (Figure 5(g)). Therefore, we also attempt to increase $C_r$ to 1.5 and 2, which means 50% or 100% of the cracks are covered by other foreground/background clouds along our sight lines. As shown in Figures 5(d) and (g), the $R_{\text{ion}}$ distributions of the model with the $C_r = 2$ (Model P in Table 3) and the model with the diffuse gas (e.g., Model K in Table 3) are very similar to each other. Because there are no cracks inside the CGM in both of the models, the one-on sample occurs only at the edge of the modeled CGM.

### 4.1. Optimized Models

After repeating the above models by changing five parameters, we select the best models for high- and low-ion samples, respectively, as shown in Figure 6 whose best parameters are summarized in Table 3. We chose the best models based on the following two criteria; (1) $R_{\text{ion}}$ values from the model and the observation are consistent to each other within $1\sigma$ errors for a wide range of $D_{\text{vir}}$, and (2) the model and the observation have the largest common areas of dEW boxes among those satisfying the first criterion. As summarized below, our best models suggest both high- and low-ion absorbers have large (or full) coverage fractions along our sight lines. However, the coverage fraction (i.e., a volume number density of gas clouds) should be inversely proportional to the distance from host galaxies (e.g., Rudie et al. 2012), while we assume a constant cloud density throughout the CGM. Our observation can be biased for regions in the vicinity of host galaxies (e.g., $\leq 100$ kpc), where the coverage fraction is probably very high.

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18. This is a typical size of N II absorbers whose ionization parameter IP = 29.6 eV is between those of C IV (64.5 eV) and Mg II (15.0 eV) (Stern et al. 2016).

19. This is large enough (five times larger) compared to the maximum scale of our observation, ~10 kpc.
First, we focus on high-ion absorbers. As shown in Figure 3, an average value of the fractional difference of equivalent widths (dEW) is obviously larger than ~0.1 at the scale of $D_{\text{tra}} \sim 0.1$ kpc, which means that there exist small-size clouds or density fluctuations at the corresponding scale. As shown in Figure 5(b), the size of each cloud should be smaller than $D_{\text{tra}}$.
The detection rate of C IV absorption lines also depends on star formation rate and stellar mass of host galaxies as well as a Mpc-scale galaxy number density around host galaxies.

\(<0.5–1\) kpc) fluctuation of EW. Compared to our best model, the past results for the CGM at \(z < 0.1\) suggested that they have a smaller overall size of \(100–200\) kpc around galaxies (Chen et al. 2001; Bordoloi et al. 2014; Burchett et al. 2016). As for the covering factor, Chen et al. (2001) obtained a similar result to ours (i.e., full coverage) within \(<100\) kpc from host galaxies, although a partial coverage was sometimes suggested even at smaller impact parameters (e.g., Bordoloi et al. 2014). The detection rate of C IV absorption lines also depends on star formation rate and stellar mass of host galaxies as well as a Mpc-scale galaxy number density around host galaxies.

Table 3

| Model          | Function\(^a\) | \(d\) (kpc) | \(L\) (kpc) | \(EW_{\text{diff}}\) | \(C_i\) |
|----------------|----------------|-------------|-------------|----------------------|--------|
| (1)            | (2)            | (3)         | (4)         | (5)                  | (6)    |
| A              | ell.           | 1           | 50          | □                   | 1      |
| B              | inv.           | 1           | 50          | □                   | 1      |
| C              | lin.           | 1           | 50          | □                   | 1      |
| D              | ell.           | 0.5         | 50          | □                   | 1      |
| E              | ell.           | 5           | 50          | □                   | 1      |
| F              | ell.           | 10          | 50          | □                   | 1      |
| G              | ell.           | 1           | 100         | □                   | 1      |
| H              | ell.           | 1           | 500         | □                   | 1      |
| I              | ell.           | 1           | 50          | 0.01                | 1      |
| J              | ell.           | 1           | 50          | 0.05                | 1      |
| K              | ell.           | 1           | 50          | 0.1                 | 1      |
| L              | ell.           | 1           | 50          | 0.5                 | 1      |
| M              | inv.           | 1           | 50          | 0.01                | 1      |
| N              | inv.           | 1           | 50          | 0.02                | 1      |
| O              | inv.           | 1           | 50          | 0.05                | 1      |
| P              | ell.           | 1           | 50          | □                   | 2      |
| Q              | ell.           | 1           | 50          | □                   | 1.5    |
| R              | ell.           | 1           | 50          | □                   | 0.5    |
| Best Model 1 (high-ion) | ell. | 1 | 500 | □ | 2 |
| Best Model 2 (high-ion) | ell. | 0.5 | 500 | 0.5 | 1 |
| Best Model 3 (low-ion) | ell. | 1 | 500 | □ | 1.5 |

Notes.

\(^a\) Function of radial distribution of equivalent width: elliptical (ell.), inverse proportional (inv.), and linear (lin.) functions.
\(^b\) Size of each absorbing cloud.
\(^c\) Overall size of the CGM in diameter.
\(^d\) Intensity of equivalent width in a diffuse gas. Three dots means no diffuse gas is added.
\(^e\) Covering factor of clouds in the CGM.

\(\sim 1\) kpc. Otherwise, \(\text{dEW}\) is underestimated at \(D_{\text{tra}} \sim 0.1\) kpc. The one-on ratio \(R_{\text{ion}}\) leaves zero only at larger scales of several kiloparsecs, which requires us to choose an overall size of the CGM larger than \(L \sim 100\) kpc (see Figure 7) once we adopt the best value for a covering factor \((C_i = 2)\) later. It is probably comparable to or larger than the overall size for low-ion absorber \((L > 500\) kpc as described below) because high-ionized absorbers usually have a larger distribution than low-ionized absorbers (e.g., Stern et al. 2016). High-ion absorbers cannot have any small-scale cracks therein because their \(R_{\text{ion}}\) is zero at \(D_{\text{tra}}\) smaller than several kiloparsecs. Based on the above considerations, we find two of the best models for high-ion absorbers. They have an overall size of \(\sim 500\) kpc or more with clumpy clouds (or density fluctuation) smaller than \(1\) kpc whose EW distribution follows the elliptical function.\(^{21}\)

They have no cracks between small clouds, which can be reproduced by either \(C_i = 2\) or a diffuse gas with an intensity of \(EW_{\text{diff}} = 0.5\) (Figure 6 and Table 3). Here, we emphasize that the best size of each cloud is \(d \lesssim 0.5\) kpc (instead of \(\lesssim 1\) kpc) in the latter case. Thus, we infer that high-ion absorbers originate in a widely distributed homogeneous gas with a scale of \(\gtrsim 500\) kpc, in which there exists a small-scale

\(^{21}\) The model using the inverse proportional function is also acceptable, but the elliptical function gives a better result.
For low-ion absorbers, dEW is almost flat at $D_{\text{ion}} \sim 0.1$–10 kpc like high-ion absorbers. Such distributions can only be reproduced by small clumpy clouds with scales smaller than $d \leq 1$ kpc (see Figure 5(b)). The one-on ratio is also flat at the same $D_{\text{ion}}$ range, which requires an overall size greater than $L \sim 500$ kpc. The covering factor ($C_f$) should be larger than 1 (to avoid an overestimation of $R_{\text{ion}}$) but smaller than 2 (to make subkiloparsec-scale gaps so that $R_{\text{ion}}$ is not zero). Our best model for low-ion absorbers has an overall size of $\sim 500$ kpc or more with small clumpy clouds (or fluctuation) with a scale of $\sim 1$ kpc. These are the same as those for high-ion absorbers. However, their covering factor is smaller ($C_f = 1.5$) than high-ion absorbers ($C_f = 2$), which means that low-ion absorbers have cracks with a scale of $\leq 1$ kpc (see Figure 6 and Table 3). This is why only low-ion absorbers have a substantial one-on ratio as small as $D_{\text{ion}} \sim 0.1$ kpc. For the same reason, low-ion absorbers do not have a homogeneous gas component (i.e., $E_{\text{diff}} = 0$). Therefore, we expect that a low-ion absorber consists of a large number of clumpy dense clouds with a scale of $\leq 1$ kpc. Again, the past results predicted a smaller size of the CGM ($\sim 200$ kpc; e.g., Churchill et al. 2013; Nielsen et al. 2013) based on Mg II absorption lines at $z < 1$, compared to our best model. The covering factor of Mg II was also estimated as $C_f \sim 0.6$–0.9, depending on an azimuthal angle; the higher covering factors along the projected galaxy major and minor axes (Kacprzak et al. 2012).

Thus, the best model above requires three components in total: i.e., clumpy clouds for high ions, clumpy clouds for low ions, and diffuse homogeneous gas for high ions. Obviously, these three components have different ionization conditions. To locate their origins, we performed simple calculations using the photoionization code Cloudy, version 17.00 (Ferland et al. 2017), on a slab of gas illuminated with extragalactic background radiation (Haardt & Madau 2012) at $z = 2.0$ (a typical $z_{\text{abs}}$ in our sample). We assume a constant metallicity of $\log(Z/Z_\odot) = -1.0$ throughout the gas whose total hydrogen column density is $\log N_H = 18.0$ cm$^{-2}$ in the optically thin regime.  

22 We varied the ionization parameter ($\log U$) in steps of 0.1 dex from -4.0 to 0.0 (which corresponds to the gas density of $\log n \sim -0.6$ to $-4.6$ at $z = 2.0$), and then calculated the ionization fractions of $\text{C}^{3+}$ ($\text{C IV}$), $\text{Mg}^{+}$ ($\text{Mg II}$), and $\text{O}^{5+}$ ($\text{O VI}$) as a function of ionization parameter ($\log U$) (bottom label) and a gas volume density ($\log n$) at $z = 2$ (top label). Photoionization models are conducted using the code Cloudy (or Clowdly) with an assumed plane-parallel slab that is illuminated with the extragalactic background radiation at $z = 2.0$. We also assume a constant metallicity of $\log(Z/Z_\odot) = -1.0$ throughout the gas whose total hydrogen column density is $\log N_H = 18.0$ cm$^{-2}$.

and $\text{O}^{5+}$ ($\text{O VI}$) (as an example of higher ionized absorbers).  

23 As shown in Figure 8, the ionization fractions of $\text{Mg}^{+}$ and $\text{C}^{3+}$ are dominant at $\log U < -3$ ($\log n > -2$) and $\log U \sim -3$ to $-1$ ($\log n \sim -2$ to $-4$), respectively, which are probably optimal for the $\text{C IV}$ and $\text{Mg II}$ absorbers. However, there are several origins including dwarf galaxy mergers, diffuse clumpy clouds, and also a size of the CGM ($L \geq 500$ kpc).

2. Only five free parameters are obviously not enough to make models. It can be improved by adding radial functions of gas density and volume density of the spherical cloud from the center of the CGM as additional parameters.

4.2. Caveats

Here, we list some caveats of our results that should be noted.

1. The source of the absorber (i.e., a host galaxy) was not identified. There are several origins including dwarf galaxy, low surface brightness galaxy, galaxy merger, galaxy outflow, AGN outflow, and so on. Without identifying host galaxies, we cannot narrow down possible sources. For the same reason, we did not make a “zero-on” sample (i.e., no absorption is detected in both sight lines even if there exist a galaxy close to our sight lines to the quasars) in addition to one-on and two-on samples because we do not know the locations of galaxies close to our sight lines in advance, which could overestimate a covering factor ($C_f \geq 1.5$) and also a size of the CGM ($L \geq 500$ kpc).

2. Only five free parameters are obviously not enough to make models. It can be improved by adding radial functions of gas density and volume density of the spherical cloud from the center of the CGM as additional parameters.  

23 In this assumption, since the gas temperature is $\sim 4 \times 10^{5}$ K, collision excitation does not substantially contribute.
free parameters. Indeed, both optical depth and EW of C IV absorption lines at $D_{\text{tra}} \sim 500$ kpc are about one order of magnitude smaller than those at $D_{\text{tra}} \sim 100$ kpc (e.g., Turner et al. 2014; Turner 2015). The CGM absorption strength also depends on physical properties of host galaxies such as luminosity, star formation rate, stellar mass, and a number density of galaxy in Mpc scale around that (Chen et al. 2001; Bordoloi et al. 2014; Burchett et al. 2016).

3. Our sample is heterogeneous in terms of spectral resolution (i.e., $\sqrt{\Delta \lambda} \sim 1000-27,000$) and data quality (i.e., a wide range of S/N). It also should be noted that strong absorption lines (REW $\sim 1-2$ Å) in our sample have two possible origins: a “single” dense gas system and a clustering of gas clumps of narrow absorption lines, although we cannot separate them into the two groups with our low-resolution spectra. It is highly required to perform the same analyses based on homogeneous (and higher resolution) spectra taken with the same telescope and instrument with a specific observing configuration.

5. Summary

We collected spectra of 13 gravitationally lensed quasars from the SDSS Quasar Lens Search catalog as well as from the literature and investigated the fractional EW difference dEW and one-on ratio $R_{\text{ion}}$ as a function of the physical separation in the transverse direction $D_{\text{tra}}$. We also constructed simple models with five parameters to reproduce the observed results based on 293 metal absorption lines to investigate the internal structure of the CGM. Our main results are as follows.

1. Correlation coefficients between absorption strength (i.e., REW) along sight-line pairs are almost the same for high-ionized lines (e.g., C IV) and low-ionized lines (e.g., Mg II), although the latter tends to have larger scatter at REW $< 1$ Å.

2. The typical size of high-ionized absorbers is probably larger than that of low-ionized absorbers because the former has a small one-on ratio ($R_{\text{ion}} \sim 2$%) only at larger physical distance between sight lines of lensed images ($D_{\text{tra}} \sim 10$ kpc), while the latter has $R_{\text{ion}} \sim 16$% at the smaller scale of $D_{\text{tra}} \sim 1$ kpc.

3. Both high- and low-ionized absorbers have almost the same values of the fractional EW difference dEW $\sim 0.2$ for a wide range of sight-line separations $D_{\text{tra}} \sim 0.1-10$ kpc, although the latter has a larger scatter of dEW.

4. We constructed simple models for the CGM using five parameters; EW distribution as a function of the radius (e.g., C IV) and the number density of gas clouds as a function of the distance from the host galaxies to improve our current models.

Comparing the models and the observations, we placed constraints on the internal structure of the CGM with acceptable ranges for five parameters. Our best model gives a picture of the CGM that is similar to those in the literature: low-ionized absorbers have a complex internal structure consisting of a large number of small-scale clouds, and they are embedded in the diffusely distributed high-ionized regions.

Our results suggest that more detailed analysis using larger samples taken with the same telescope/instrument is important to strengthen our conclusion. More lensed quasars will be discovered by deep imaging surveys like the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP; Aihara et al. 2017) with follow-up spectroscopic observations. If absorption lines are resolved completely in high-resolution spectra, we can further discuss the internal structure of the CGM based on column density (rather than EW) and velocity structure by applying Voigt profile fitting. We also need to perform deep imaging observations to detect host galaxies of our sample absorption systems to investigate the physical properties of the CGM as a function of the impact parameter from host galaxies of absorbers. By doing so, we will be able to discuss a volume number density of gas clouds as a function of the distance from the host galaxies to improve our current models.

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