Mg II Absorbers: Metallicity Evolution and Cloud Morphology

Ting-Wen Lan1 and Masataka Fukugita1,2

1 Kavli Institute for the Physics and Mathematics of the Universe, University of Tokyo, Kashiwa, Chiba 277–8583, Japan
2 Institute for Advanced Study, Princeton, NJ 08540, USA

Received 2017 July 30; revised 2017 October 11; accepted 2017 October 12; published 2017 November 28

Abstract

Metal abundance and its evolution are studied for Mg II quasar absorption line systems from their weak, unsaturated spectral lines using stacked spectra from the archived data of the Sloan Digital Sky Survey. They show an abundance pattern that resembles that of the Galactic halo or Small Magellanic Cloud, with metallicity [Z/H] showing an evolution from redshift z = 2 to 0.5: metallicity becomes approximately solar or even larger at z ≈ 0.

We show that the evolution of the metal abundance traces the cumulative amount of the hydrogen fuel consumed in star formation in galaxies. With the aid of a spectroscopic simulation code, we infer the median gas density of the cloud to be roughly 0.3 cm−3, with which the elemental abundance in various ionization stages, in particular C i, is consistently explained. This gas density implies that the size of the Mg II clouds is of the order of 0.03 kpc, which suggests that individual Mg II clouds around a galaxy are of a baryonic mass typically 10^3 M⊙. This means that Mg II clouds are numerous and “foamy,” rather than a large entity that covers a sizable fraction of galaxies with a single cloud.

Key words: galaxies: halos – quasars: absorption lines

1. Introduction

Mg II quasar absorption clouds ubiquitously reside in the vicinity of galaxies, typically within their virial radii, in circumgalactic space (Bergeron & Boissé 1991; Steidel et al. 1994). The absorption features at intervening redshifts are detected from 35% to 40% of quasar spectra (e.g., see Zhu & Ménard 2013 for modern SDSS data) and Mg II clouds cover as large as 50% of the sky around galaxies typically at redshift ~0.5 (e.g., Chen et al. 2010; Ménard & Fukugita 2012; Nielsen et al. 2013; Lan et al. 2014). We expect the clouds to be affected by neighboring galaxies, yet their nature and formation are not known well, because our knowledge of the cloud is limited to line-of-sight observations. The feature we now know is that Mg II clouds are significantly contaminated with metals, harboring dust (e.g., York et al. 2006; Ménard & Fukugita 2012), whereas star formation activity therein is not known, nor expected given the low column density of the clouds. The morphology of the clouds is also yet to be known: whether they consist of several large clouds that cover a significant fraction of galaxies, or an assembly of small clouds.

Elemental analyses for these clouds are often hampered by the fact that important metal lines are saturated, whereas weak lines suffer from poor signal-to-noise ratios to carry out a detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis.

Elemental analyses for these clouds are often hampered by the fact that important metal lines are saturated, whereas weak lines suffer from poor signal-to-noise ratios to carry out a detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis. In the present work, we explore metal lines, using weak, unsaturated lines by stacking many spectra to give detailed analysis.

Our data analysis is written in Section 2 to measure the equivalent width, with some results in our intermediate steps given in the Appendix. We discuss in Section 3 the column density of elements that show absorption features in Mg II clouds. The CLOUDY code was employed to infer the physical state of the gas in the clouds. In this work, all equivalent widths referred to are those in the rest frame. Wherever we refer to the average value, we take median quantities to avoid largely deviated data unless otherwise explicitly stated. When we refer to the solar composition, it is that by Asplund et al. (2009). Section 4 is given for the summary of our analysis. We use H_0 = 70 km s^{-1} Mpc^{-1}, and Ω_M = 0.3 in a flat universe. W_{λ2796} refers to the rest equivalent width of the Mg II λ2796 line.

2. Data Analysis

2.1. Composite Spectra for Metal Absorption Lines

We use the metal absorber catalog3 and the corresponding spectra compiled by Zhu & Ménard (2013) from quasar spectra of the Sloan Digital Sky Survey I-III (York et al. 2000). The sample contains 77,647 Mg II absorbers from redshift 0.4 to 2.5, detected in 142,012 quasar spectra from the DR7 (Schneider et al. 2010) and DR12 (Pâris et al. 2017) quasar catalogs. In the present study, we take 70,713 systems with W_{λ2796} > 0.4 Å. The completeness of Mg II absorbers drops gradually from W_{λ2796} = 0.8 Å and it is about 30% at W_{λ2796} = 0.4 Å. The completeness is not an important issue in major parts of our analysis.

We make median composite spectra of Mg II absorbers divided into bins of their absorption strengths, as characterized with Mg II λ2796 and redshifts. We focus on rest-frame wavelengths longer than 1250 Å. The median estimator is used to avoid too strong effects of outliers in spectra that occasionally occur. We emphasize that it is essential to our work to measure weak unsaturated absorption lines accurately.

---

3 http://www.guangtunbenzhu.com/jhu-sdss-metal-absorber-catalog
The metal absorption lines we measure are listed in Table 1 below. The typical signal-to-noise ratio of the composite spectra per spectral resolution element (70 km s$^{-1}$) is about 500, which allows us to measure absorption features to the level of 0.01 Å in equivalent widths.

We measure the rest-frame equivalent widths of isolated metal lines with a single Gaussian profile fitting. For wavelength regions with multiple lines crowded, we adopt multiple Gaussian profiles to fit all relevant absorption lines in both vicinity of lines and continuum. A special treatment is used to obtain the rest equivalent widths of Zn II to deblend lines of Cr II and Mg I (e.g., York et al. 2006). The errors of the rest equivalent widths are estimated by bootstrapping the sample 200 times. In the Appendix, we show an example of the composite spectra, the Gaussian profile fitting, and the measured rest equivalent widths of metal lines as a function of redshift and Mg II strengths.

For weak absorption lines, we can estimate the column density with the linear relation of the curve of growth.
strength monotonically with redshifts, as noted in Ménard & Chelouche (2009) and Matejek et al. (2013).

These trends are summarized as
\[ N_{\text{HI}} = A \left( \frac{W_{\lambda_{2796}}}{1 \text{ Å}} \right)^{1.9} (1 + z)^{3}. \] (2)

where \( W_{\lambda_{2796}} \) refer to Mg II \( \lambda 2796 \). From the fits to three separate samples for different redshift bins we find that slopes for the \( W_{\lambda_{2796}} \) dependence are mutually consistent within errors. We, therefore, adopt a common parameter \( \alpha \) for the slope for our full sample analysis. To make use of all the information, we obtain the final best-fit parameter values through a fitting to all the individual data points \( \text{log} N_{\text{HI}}, W_{\lambda_{2796}}, z \).4

The neutral hydrogen column densities increase with the Mg II equivalent width with a power index \( \alpha = 1.69 \pm 0.13 \). For the other parameters, we find \( \beta = 1.88 \pm 0.29 \) and \( A = 10^{18.96 \pm 0.10} \text{ cm}^{-2} \), which are also given in Table 1. The errors are estimated by bootstrapping the samples 200 times. The fits are presented in Figure 1 for the three redshift bins, with median redshifts 0.6, 1.2, and 3.4.

3.2. Metals in Mg II Absorbers

Having measured the rest-frame equivalent width of each absorption line for the composite spectrum for bins of the subsample, where the Mg II equivalent width and the redshift are specified, we fit our data with
\[ W_{\lambda} = C \left( \frac{W_{\lambda_{2796}}}{1 \text{ Å}} \right)^{\alpha} (1 + z)^{3}, \] (3)

where \( \alpha, \beta, \) and \( C \), are given in Table 1, and also displayed in Figure 2, where the plots are basically divided into two classes, saturated (red) and unsaturated lines (blue). The green symbols stand for the parameters for H I obtained above and that for dust reddening parametrized in a similar way as to \( \alpha \) and \( \beta \), i.e., \( E(B-V) \) in place of \( W_{\lambda} \), written in the form as Equation (3) (Ménard et al. 2008; Ménard & Fukugita 2012).5 We show the measured rest equivalent widths and the best-fit functions in the Appendix.

The following trends are seen in Figure 2.

1. All metal absorption lines (with an exception of O I) show negative \( \beta \), meaning an absorption stronger at lower redshift when measured at a fixed Mg II equivalent width. This indicates that the equivalent widths, or column densities, in the case of unsaturated lines, decrease approximately, in median, by a factor of 1.6 from redshifts 0.5 to 2.

This contrasts to neutral hydrogen, a larger equivalent width at higher redshift (\( \beta \approx 1.9 \)).

2. Most of the low-ionized, unsaturated absorption lines show \( \alpha = 1.4 \) - 1.7 with a median \( \sim 1.6 \), which is consistent with \( \alpha \) for \( N_{\text{HI}} \). Namely the abundances of metals in the line of sight is proportional to neutral

\[ \text{log} N_{\text{HI}} \propto W_{\lambda_{2796}}^{1.7 \pm 0.1} (1 + z)^{1.9 \pm 0.3}. \]

\[ 2.2 < z < 4.5 \]

\[ 0.9 < z < 1.7 \]

\[ 0.1 < z < 0.9 \]

\[ \text{(e.g., Draine 2011)} \]

\[ N_{\text{ion}} \text{ [cm}^{-2}] = 1.13 \times 10^{20} \times \frac{W_{\text{ion}}}{\lambda_{\text{rest}}}, \] (1)

where the oscillator strength \( f \) is from Morton (2003) and \( \lambda \) (Å) the rest-frame wavelength of the absorption line. For weak unsaturated lines, we give in Table 1 (Column 3) the estimated column density. By comparing measurements with the theoretical curve of growth, we confirm that those absorption lines are in the linear regime. The strong, saturated absorption lines are marked in column (3) with an asterisk.

3. Results

3.1. Evolution of the H I Column Density in Mg II Absorbers

Let us first study neutral hydrogen in Mg II absorbers. We additionally take Mg II absorber samples with neutral hydrogen column densities measured with the Voigt fitting to study their H I content: (i) the \( z \sim 1 \) sample from Rao et al. (2006), which consists of 197 Mg II absorbers at \( z < 1.7 \) with \( N_{\text{HI}} \geq 10^{18} \text{ cm}^{-2} \); (ii) the high-redshift \( (z \sim 3) \) sample from Matejek et al. (2013), containing 33 systems with median redshift about 3.4. These are supplemented by (iii) the recent low-redshift \( (z \sim 0.3) \) sample of 16 Mg II absorbers in Rao et al. (2017).

Figure 1 shows the samples as blue \( (z \sim 0.6) \), green \( (z \sim 1.2) \), and red \( (z \sim 3.4) \) symbols, taken from the references cited above. We also show the median values of the samples with bootstrapping errors shown with square data points. We observe that the column densities of neutral hydrogen increase with the equivalent widths of Mg II absorption lines (Mg II \( \lambda 2796 \)), and at a fixed Mg II absorption

4 We have obtained the best-fit parameter values with three methods, (1) fitting to all the individual data points, (2) fitting to median values with bins, and (3) fitting to mean values with bins, and confirmed that the three methods yield consistent best-fit parameters.

5 The fit here refers to the rest-frame color, as in Ménard et al. (2008), while a similar fit of Ménard & Fukugita (2012) uses the color in the observed frame. The power indices of the two differ by 1.2, reflecting the \( \lambda^{-1.5} \) dependence of the extinction curve.
hydrogen column density, or, in other words, metallicity of MgII clouds does not vary much with $W_{2796}$.

We remark that $\alpha$ of ZnII is somewhat larger, $\alpha \sim 2$, which is about $3\sigma$ away from the remainders.

3. C I absorption shows that both $\alpha$ and $\beta$ are largely different from other lines. The $\beta \sim -3.9$ value indicates that the C I equivalent width decreases by more than a factor of 5 from redshifts 1 to 2.5. We will pay special attention to C I below.

4. Low-ionized saturated absorption lines, MgII, C II, and Si II are nonevolving: $\beta \approx 0$. The $\alpha$ values being close to 1 means a similarity to our reference MgII absorption line. This is expected for the saturated rest equivalent width, which is controlled by the velocity dispersion of the system.

5. Highly ionized absorption lines, C IV and Si IV, are saturated. They show $\alpha \sim 0.6$ and $\beta \sim -1$ that differ from low-ionized saturated lines.

---

**Figure 2.** Dependence of the equivalent width of each absorption line upon the strength of the MgII absorption line ($W_{2796}$), $\alpha$, and redshift, $\beta$, as parametrized in Equation (3). Blue symbols indicate weak unsaturated lines and red symbols are for saturated lines. Purple symbols highlight Si II, Fe II, Zn II, and C I which are discussed in the text. Green symbols are used for the hydrogen column density and for extinction $E(B-V)$.

**Figure 3.** Abundance of each element relative to Zn as a function of redshift. The last panel shows the dust abundance as estimated from $E(B-V)$ divided by the column density of Zn II. Horizontal lines indicate the corresponding value for the Milky Way halo (green) and for interstellar matter (orange; York et al. 2006). The zero point is the solar value. Blue points refer to the relative abundance with no ionization correction, $[X/Zn] = [X II/Zn II]$ and gray points refer to the relative abundance after the ionization corrections are taken into account.
6. We added $E(B - V)$ for a reference, taken from Ménard & Fukugita (2012). $\alpha \approx 1.6$ means $E(B - V) \propto N_{\text{H}_1}$, and $\beta - 1.2$ is consistent with the decrease of metallicity to higher $z$.

In Figure 3, we show the evolution of the abundance pattern for several representative heavy elements in the single ionized state in Mg II absorbers with $W_{2796} > 0.8$ Å, as a function of redshift, taking the column density of Zn II as the reference. At this stage, we do not apply ionization corrections, which turn out to be appreciable for Zn II, to facilitate their comparison with elemental abundance in the literature, in which ionization corrections are usually not made. The zero point of the ordinate is the solar. Horizontal dashed lines show the abundance taken from York et al. (2006), representing the value in the Milky Way’s halo, which is similar to the SMC abundance (Welty et al. 2001), and that of cold interstellar matter. The figure shows the abundance in Mg II clouds is similar to that in the Milky Way halo, in agreement with what was argued in York et al. The abundance is not in agreement with that of the interstellar medium of the Milky Way. It deviates from the solar, but they become close if they are shifted by 0.5 dex (0.2 dex for Si II) upwards. The relative abundance is also listed in Table 2. The upper part shows values without ionization correction and the lower part lists values for Mg II clouds with ionization correction taken into account, which will be discussed in Section 3.3 below.

The 0.5 dex smaller abundance of the iron group elements is likely to be ascribed to the condensation into grains. Si is also smaller than solar by 0.2 dex, as is the abundance in the halo, which is also ascribed to depletion onto grains. The metal abundance relative to Zn evolves weakly in the redshift range we study.

The lower rightmost panel shows the dust abundance divided by the Zn II abundance, where $E_{B-V} \approx 0.01(W_{2796}/1\AA)^{1.6}$ $(1 + z)^{-1.2}$ is used for the proxy for dust (Ménard et al. 2008; Ménard & Fukugita 2012). This dust to metal in gas ratio is close to the Milky Way’s value (Wild et al. 2006), but is significantly larger than the values in SMC or in Milky Way halo by a factor of 3.

3.3. Physical Conditions and Ionization Corrections

We have derived the column density of metals in their ionized state. For Fe II, Si II, etc., these are predominant ionization states and they represent practically the full column density of those heavy elements. For other states, however, we must know the physical state to infer how many fractions are in specific ionization stages. When compared with the observation, this in turn tells us about the physical conditions of Mg II absorbers. The other uncertainty arises from condensation into grains, as seen for iron and silicon.

We employ the CLOUDY code (Ferland et al. 2013) to infer the ionization correction factor for the given physical condition. We take the hydrogen column density $N_{\text{H}_1}$, the volume density of hydrogen $n_{\text{H}_1}$, and metallicity of gas as parameters. We set the relative element abundance pattern to the Milky Way halo value listed in Table 2. We find that the ionization correction for Zn II is appreciable, while it is not for Fe II, Mg II, etc.

We assume that the cloud is photoionized by the background radiation field, using the 2005 version of Haardt & Madau cosmic background radiation field at each redshift, as in the default setting in CLOUDY. We constrain CLOUDY simulations with the neutral hydrogen column density consistent with Mg II absorbers as observed, and explore $n_{\text{H}_1}$ and metallicity that reproduce the column densities of Fe II, Ni II, C I, Al III, Cr II, Zn II, and Mg I as we observed. To constrain the physical conditions, we use measurements with high S/N derived from composite spectra with Mg II absorbers with $W_{2796} > 0.8$ Å in this section. We have also carried out the analysis as a function of $W_{2796}$ and confirmed that the inferred physical conditions have a weak dependence with $W_{2796}$.

Table 2 shows an example of several metal column densities (Si II, Fe II, C I, C II, Zn II) at $z \approx 1.5$ from CLOUDY as a function of the gas density $n_{\text{H}_1}$, compared with the observed values. Solar metallicity $[Z/H] = 0$ is assumed. The observed column densities are also indicated by horizontal lines, together with the observation shown in the right margin. We see that the calculation becomes close to the observation for almost all elements we consider when $-1 < \log n_{\text{H}_1} < 0$. We carry out this analysis at redshifts between $z = 1$ and 2.5. We find that features of the curves of the metal column density versus $n_{\text{H}_1}$ change only at a quantitative level in this redshift interval. We note that C I is particularly sensitive to the hydrogen volume density of the system, and also to redshift. Let us note that C I is a minor component, while C II is the predominant agent of carbon.

---

**Table 2**

Relative Abundance Patterns of Mg II Clouds, Milky Way halo, SMC, and Milky Way ISM

| [X/Zn] | [X II/Zn II] | C | Si | Mg | Fe | Cr | Ni | Mn | Ti | Reference |
|--------|-------------|---|----|----|----|----|----|----|----|----------|
| Mg II clouds | ... | −0.2 | ... | −0.5 | −0.5 | −0.5 | −0.7 | −0.6 | This paper |
| Milky Way halo | −0.2 | −0.2 | −0.5 | −0.5 | −0.5 | −0.5 | −0.6 | −0.6 | York et al. (2006) |
| SMC (sk 108) | ... | 0.1 | ... | −0.5 | −0.5 | −0.8 | −0.6 | ... | Welty et al. (2001) |
| Milky Way cool ISM | 0.1 | −0.9 | −0.8 | −1.8 | −1.7 | −1.8 | −0.9 | −2.4 | York et al. (2006) |

Notes.

* The ionization correction for Zinc, log $N_{\text{Zn}_2} \approx \log N_{\text{Zn}_{2\text{\text{II}}}} + 0.4$, is estimated with log $n_{\text{H}_1} = -0.5$.
* Assuming Milky Way halo values with ionization correction.

---

http://trac.nublado.org/wiki

This is an unpublished update of their 2001 version (Haardt & Madau 2001). There is an alternative choice of the cosmic background radiation field Haardt & Madau (2012), which gives a photon spectrum somewhat tilted from their 2005 version. We have also carried out our analysis with the radiation field of Haardt & Madau (2012), which yielded metallicity by 0.2—0.3 dex higher ($n_{\text{H}_1}$ is lower by 0.3 dex). Because of this resulting supersolar metallicity, which looks unphysical, we do not take this 2012 version as our setting.
We attempt to simultaneously constrain the volume density and the metallicity with the observed Zn II column density and the ratio of N(C I) to N(C II), as shown in Figure 5 for 1σ and 2σ contours at z \approx 1.5. The hydrogen volume density is about log n_H \approx -0.5 and metallicity is consistent with the solar.

In Figure 6, we show the redshift evolution of C I from CLOUDY, which shows a rapid decrease with redshift, where we assume log n_H = -0.5 for all redshifts. The rapid evolution of C I agrees very well with that we derived from the observation.

We then estimate the major component, C II abundance N(C II) from N(C I) using the ionization correction factor. The C II column density thus calculated is nearly constant in our redshift range, where the ionization correction factor for C I varies rapidly between 100 and 1000. We compare it with N(C II) estimated from N(Si II) with the Milky Way halo abundance ratio of carbon to silicon. The agreement of the two estimates is impressive, verifying the validity of CLOUDY results with the 2005 version of the Haardt & Madau ionization field at each redshift.

We now lift the assumption of log n_H = -0.5 for all redshifts, and obtain the best fit at each redshift bin using N(H I), N(C I)/N(C II) and N(Zn II) as constraints. Figure 7 shows log n_H = -0.5 \pm 0.1 at all redshifts that concern us. This indicates that a strong redshift evolution of C I column density, N(C I) \propto (1 + z)^{-3.9}, is induced most importantly by a decrease of photoionizing radiation field toward lower redshifts. This fast evolution of C I column density accounts for a rapid evolution of the C I cloud incidence, a rapid increase from z = 2.5 to 1.5 observed in Ledoux et al. (2015).

We also study the prediction of Al III, Zn II, and Mg I column densities. We find that the observed Al III column density is consistent with the prediction for -1 \leq log n_H \leq -0.5. The CLOUDY result for Zn II is consistent with the observation in so far as -1 \leq log n_H \leq 0.5. So, our choice, log n_H \approx -0.5, from C I is a compromise, consistent with the observation for

**Figure 4.** Column density of various species: comparisons are made of the observed values (the symbols in the rightmost and horizontal lines extended therefrom) against the CLOUDY simulation plotted with varying hydrogen volume densities.

**Figure 5.** Allowed region for metallicity [Z/H] and the gas density log n_H at redshift z \approx 1.5 constrained by the observed N(H I), N(C I)/N(C II), and N(Zn II).

**Figure 6.** Redshift evolution of the column density of neutral carbon in Mg II absorbers: observed (blue symbol) vs. CLOUDY simulation (red shades), shown in the lower part of the figure. In the upper part, the C II column density calculated from C I with the ionization correction factor is shown together with C II from Si II using the Milky way halo abundance composition.
Al III and Zn II. On the other hand, the CLOUDY calculation overestimates the observed Mg II column densities by about 0.25 dex for log n_H that concerns us. There seems to be no consistent value of log n_H. This discrepancy suggests that the input, including the background radiation field, may not fully capture the relevant physics for Mg I, as was also noted by Prochaska et al. (2017). The major components, Si II, Fe II, Cr II, and Ni II, vary little against each other. We estimate the heavy element abundance relative to Zn estimated from Zn II: log N Zn II ∼ log N Zn II + 0.4. We showed the resulting Z/Zn in Figure 3 above. After ionization corrections for Zn II, the depletion of the iron group elements becomes e.g., [Fe/Zn] ∼ [Fe II/Zn II] ∼ −0.4 ∼ −0.9 dex, rather than 0.5 dex, and that for silicon is −0.6 dex, rather than 0.2 dex: see the gray symbols in the figure and the lower part of Table 2.

We find from CLOUDY that n H1/n H1 = 0.8–0.9 for log n_H = −0.5, hydrogen predominantly being neutral. The inferred temperature of the cloud is about 2500 K with about 300 K uncertainty. The neutral fraction stays at greater than 0.5 unless n H becomes smaller than −1.5, for which temperature goes up to greater than 5000 K. These results change weakly with redshift.

The derived volume density of H I has a significant implication concerning size of the Mg II cloud. It implies that cloud sizes are of the order of r cloud ∼ N H1/n H1 ∼ 0.03 kpc, much smaller than the size of galaxies. This is consistent with the spatial size inferred for one specific cloud, showing Si II and C II absorption features, from a gravitationally lensed quasar (Rauch et al. 1999). The spatial size inferred for one speci c cloud, showing Si II, but not C II absorption features, from a gravitationally lensed quasar (Rauch et al. 1999). For this size, we infer the typical baryonic mass of Mg II clouds of the order of M cloud ∼ 10^3 M_.. Considering the fact that the covering factor of Mg II clouds around galaxies at redshift ∼0.5 are typically 0.5 (e.g., Chen et al. 2010; Ménard & Fukugita 2012; Nielsen et al. 2013; Lan et al. 2014), at a distance typically 20–50 kpc from the galaxy center. This size means that Mg II clouds that surround galaxies should be numerous, say, at least 10^5–10^6. So, they are like patchy clouds or foam-like objects that surround galaxies. This is also consistent with multiple components of Mg II clouds in the velocity space seen in many sight lines to quasars, as observed in Churchill et al. (2003).

3.4. Cosmic Mass Density of Metals

The cosmic mass density of H I in Mg II clouds is estimated from

\[ \rho_{H I}^{Mg II}(z) = \frac{m_{H I}}{dX/dz} \int_{W_{min}}^{\infty} dW_{2796} \frac{dN}{dW_{2796}} \times N_{H I}(W_{2796}, z), \]

where dN/dW_{2796} dz is the incidence rate of Mg II absorbers (taken from Zhu & Ménard 2013), and N_{H I}(W_{2796}, z) is the H I column density we derived in Equation (2): X is the absorption distance. We take W_{min} = 0.4 Å as a default. We study the convergence of the integral toward the weak line limit. We find a 30% decrease of Si II if W_{min} is increased to 0.8 Å. Our extrapolation to W_{min} = 0 indicates the increase of the integral from the 0.4 Å cutoff to be at most a few percent in \rho_{H I}; the integral is fairly well convergent with our default W_{min}. The H I mass density obtained in Equation (4) decreases toward zero redshift, as shown in Figure 8: \( \Omega \simeq 4 \times 10^{-4} \) at \( z = 2 \) decreases to \( 1 \times 10^{-4} \) at \( z = 0.5 \). This estimate is consistent with Ménard & Fukugita (2012).

We estimate the mass density of various elements in respective ionization stages, or the density of species after the ionization correction, by replacing H I with the relevant element and state in Equation (4). In Figure 8, we show the cosmic mass density residing in the Mg II cloud for various species, C II, Mg II, Si II, Fe II, Ni II, C I, Al III, Cr II, Mn II, Zn II, Ca II, Mg I, and Ti II. For most of the specific elements, those ionization stages depicted in the figure stand for the predominant state in the cloud. We note that the curve for Si II is degenerated with that of Mg II, including the redshift dependence. We also add a curve corrected for the depletion for Fe, total heavy element abundance (Metals) in Mg II clouds taking the solar composition, and dust abundance in Mg II clouds from Ménard & Fukugita (2012).

The cosmic density of Fe from our spectroscopic analysis after the 0.9 dex depletion correction is about \( \Omega_{Fe}^{dust} \simeq 4 \times 10^{-7} \) at \( z \approx 1.5 \), as seen in Figure 8. The 0.9 dex depletion observed in the gas phase means that about 90% of Fe (\( \Omega_{Fe}^{dust} \approx 3.6 \times 10^{-7} \)) is locked in dust grains if the origin metal composition is assumed to be solar. It would be interesting to compare this amount with the estimate from dust in Mg II absorbers. In Ménard & Fukugita (2012), the amount of dust in Mg II absorbers is estimated to be \( \Omega_{Fe}^{dust} = 2.0 \times 10^{-6} \) (\( z = 1.5 \)) from dust reddening behind Mg II absorbers using broadband quasar photometry (green data points). With a typical iron fraction of Fe/dust \( \approx 0.2 \gwe do we find \( \Omega_{Fe}^{dust} \approx 4 \times 10^{-7} \) in agreement with our spectroscopy-based estimate.\footnote{We take dust to consist of 70% astronomical silicate and 30% graphite (e.g., Draine 2011).}
The increase of mass density of metals, as borne by Mg II clouds is moderate toward \( z = 0 \). We note, however, that the H I mass density is significantly decreasing toward lower redshift, by a factor of 4 from \( z = 2 \) to \( z = 0.5 \). This means a loss of material in Mg II clouds, say, for example, by their falling on galaxies or destruction for some reason. This means that heavy elements in Mg II clouds are most likely lost along with H I gas. In other words, if we correct for this loss factor, the evolution of metal abundance should be traced by \( Z/H \), rather than \( Z \); the increase of the metal abundance toward lower redshift should then be significant.

The same comment also applies to the dust abundance in Ménard & Fukugita (2012), which shows a slow evolution with redshift. The cosmic evolution of dust should be obtained by dividing their values with the mass density of H I, correcting for the gas mass loss in Mg II clouds toward low redshift.

### 3.5. Evolution of the Global Metal Abundance

We study the metallicity evolution traced by Mg II absorbers. Namely, the measure of metallicity, \( Z/H \), stands for the abundance of heavy element that would be contained in Mg II clouds. When a correction is taken into account for the redshift evolution of hydrogen mass density in Mg II clouds, we are led to the global abundance of metals.

The resulting \( [Z/H] \) (denoted by blue solid circles in Figure 9) evolves from redshift 2.5 to 0.5, increasing by a factor of 4. This quantity can be interpreted as ordinary metallicity \( [Z/H] \). It reaches close to solar, in fact, approximately twice the solar metallicity at zero redshift.

In this figure, we compare \( [Z/H] \) of Mg II absorbers with other cool gas absorbers. The similar pattern of the evolution seen with Mg II absorbers is seen in that of DLAs (green points) (Rafelski et al. 2012) and of sub-DLAs (gray points; Quiret et al. 2016). It is important to note that the ionization correction was not usually applied to the data of DLA and sub-DLA. The correction would raise those curves approximately by 0.4 dex for sub-DLA (see also Som et al. 2015), for which we expect the physical condition is similar to Mg II clouds. In our result of Mg II, the ionization correction, most importantly that for Zn II, is included that shifted the curve upwards by about 0.4 dex.

Metallicity of Mg II clouds, with or without the ionization correction, is larger than that of DLA. It is only about 0.2 dex larger than metallicity of sub-DLA, but larger by \( \approx 1 \) dex than that of DLA. This approximately agrees with Fukugita & Ménard (2015), which shows that metallicity is inversely proportional to \( N_{\text{HI}} \) in DLA.

We show in this figure the cumulative amount of fuel used for the star formation rate in galaxies (the star formation rate is taken from Behroozi et al. 2013 integrated from a high to the relevant redshift—red dashed line—with an arbitrary normalization). It is interesting to observe that \( [Z/H] \) of Mg II clouds, i.e., what traces the total amount of metals in intergalactic media, closely traces the cumulative fuel consumed to that redshift. Metals are produced in stellar evolution: if a constant fraction of metals produced in stars is transported to intergalactic space by the galactic wind, it will contaminate circumgalactic space. Hence, it is natural to suppose that metallicity in circumgalactic space, and so in Mg II clouds, is proportional to cumulative star formation in galaxies (Ménard & Fukugita 2012).

---

8 In this figure, all errors are by bootstrapping. For DLA and sub-DLA data points, we estimate the median metallicity of their samples with bootstrapping error bars of metallicity instead of the hydrogen weighted metal abundances.
We note that the metal abundance shown in Figure 8 above refers to that contained in Mg II clouds. We must correct for the loss of gas mass in the Mg II clouds toward low redshift to obtain the global metal density evolution. Namely, we must divide each component of $W_{\rm MgII}$ by $W_{\rm HI}$.

4. Summary

Large databases of quasar absorption lines have enabled a spectroscopic study of the elemental abundance by stacking weak, unsaturated lines, such as Fe II, Zn II, C I, Si III, N I III, and so on, of many quasars as a function of line strengths of the Mg II lines but also of redshift.

We find that the abundance pattern of Mg II clouds resembles that of the Galactic halo or of SMC, but it differs significantly from solar or that of Galactic interstellar matter, as has been inferred from the extinction curve (York et al. 2006; Fukugita & Ménard 2015). We find, however, that the total abundance of heavy elements is larger than that of SMC and is close to that of the Milky Way. We also confirm that iron group elements are significantly (approximately 0.9 dex) depleted in cloud spectra, as is known in interstellar gas or in DLA (van Steenberg & Shull 1988; Pettini et al. 1994). On the other hand, depletion of zinc is, if at all, not significant, since the zinc abundance, or when it is multiplied with Z/Zn, is extrapolated to solar at $z = 0$. Therefore, we have taken zinc as our reference for metals, in agreement with earlier reports, however, after the ionization correction for Zn II is taken into account. The ratios, Fe/Zn, Si/Zn, etc., which are consistently smaller than solar due to depletion, evolve weakly with redshift.

We find a significant evolution of metallicity $Z/H$ in Mg II clouds from our highest $z = 2.5$ to the lowest $z = 0.5$, an increase by a factor of 4. We find that this is mainly caused by a decrease of total H I column density or the H I abundance of clouds toward lower redshift. We argue that the evolution of cosmic metal abundance reflects in $Z/H$ with the denominator taking account of the evolution of neutral hydrogen in Mg II clouds. Figure 9 shows that the evolution of $Z/H$ closely traces the cumulative amount of hydrogen fuel used for star formation in galaxies: evolution of metals in Mg II clouds reflects star formation of galaxies.

Among the heavy elements, we studied the species that shows a rapid evolution is C I, which exhibits an increase by a factor of a dex toward a low redshift ($z = 0.5$) in its column density, caused mainly by the decrease of the ionizing radiation. This accounts for a rapid increase of the C I cloud incidence toward low redshifts reported in Ledoux et al. (2015).

Net H I gas bound in the Mg II clouds evolves from $410 4 \times 10^{-4}$ at $z = 2$ to $1 \times 10^{-4}$ at $z = 0.5$. We also estimate the mass density of various elements. In addition, we show that the iron abundance in dust inferred from the depletion in gas phase $410 7 \times 10^{-5}$ agrees with the iron abundance inferred from dust in Mg II clouds using reddening of quasars behind the cloud.

With the aid of the CLOUDY code, we infer that the volume density of the gas is roughly $0.3 \, \text{cm}^{-3}$, which does not vary with redshift. This conclusion rests on the validity of CLOUDY calculations, but we are convinced of its reliability from the fact that it infallibly gives reasonable elemental abundance in so far as we have tested. In particular, the carbon abundance estimated from largely redshift-dependent C I becomes consistent with a constant after the use of the ionization correction factor of CLOUDY, and the carbon abundance agrees with the predominant component C II, inferred from the Si II abundance. Moreover, with this density, the evolution of the C I column density as given by CLOUDY shows nearly a perfect match.
with that observed in our redshift range. The $n_H$ dependence of Zn II, and Al III also matches well between CLOUDY and the observation with this gas density, and we find $n_H \approx 0.3 \text{ cm}^{-3}$ is a compromise to account for ZnII and AlIII.

The abundances in single ionized metal elements, such as Si II, Fe II, Ni II, etc, are also in good agreement between CLOUDY and our observation with the Milky Way halo/SMC abundance pattern. These calculations also tell us that hydrogen in the Mg II clouds is predominantly ($\approx 80\% - 90\%$) in the H I state and the temperature is estimated to be roughly 2500 K. Our elemental analysis overall seems to verify a validity of CLOUDY in our problem. We stress that CI serves as a sensitive indicator for the physical condition.

Our derived volume density of gas $0.3 \text{ cm}^{-3}$ implies, together with a typical column density of the clouds $3 \times 10^{21} \text{ cm}^{-2}$, that the size of clouds being 0.03 kpc, which is compatible with earlier inference (Rauch et al. 1999; Rigby et al. 2002; Prochaska & Hennawi 2009; Crighton et al. 2015). If this is a typical size in one dimension, numerous, say $10^6$, clouds are needed to explain the observational indication that the covering factor of MgII clouds around galaxies amounts to 50% of the sky. This means that Mg II clouds are like foam that surrounds the galaxies. This picture would explain what was found in spectroscopic observation showing multi-components of the cloud in many lines of sight (Churchill et al. 2003). Typical baryonic mass of Mg II clouds is of the order of $10^3 M_{\odot}$.

We thank Brice Ménard and Guangtun Zhu, who made their Mg II catalog and absorption spectra available to us in a digital form. M.F. thanks Hans Böhringer and Yasuo Tanaka for the hospitality at the Max-Planck-Institut für Extraterrestrische Physik and also Eiichiro Komatsu at Max-Planck-Institut für Astrophysik, in Garching. He also wishes to thank Alexander von Humboldt Stiftung for support during his stay in Garching, and the Monell Foundation in Princeton at the Institute for Advanced Study. He received in Tokyo a Grant-in-Aid (No. 154300000110) from the Ministry of Education. Kavli IPMU is supported by World Premier International Research Center Initiative of the Ministry of Education, Japan.

**Appendix**

This appendix describes the details of our analysis discussed in Section 3.1. To detect and measure weak unsaturated lines, we first make median composite spectra by grouping the sample in absorber redshift and $W_{\lambda 2796}$ bins. Figure 10 shows a composite spectrum obtained by combining 8097 individual spectra from MgII absorbers at redshift $1.6 < z < 1.9$ and $W_{\lambda 2796} > 0.8 \text{ Å}$. The black and blue spectra are identical and shown to emphasize absorption features in two scales. The y-axis scales for black and blue spectra are shown on the left and right, respectively.

Figure 10. Example of composite spectrum. It is obtained by combining 8097 individual spectra from MgII absorbers at redshift $1.6 < z < 1.9$ and $W_{\lambda 2796} > 0.8 \text{ Å}$. The black and blue spectra are identical and shown to emphasize absorption features in two scales. The y-axis scales for black and blue spectra are shown on the left and right, respectively.
Figure 11. Example of the Gaussian fittings for metal absorption lines. The observed composite spectrum is in blue and the red curves are the best-fit Gaussian profiles.
Figure 12. Rest equivalent widths of 43 metal absorption lines as a function of redshift and $W_{2796}$. The color indicates $W_{2796}$ from weak (cyan) to strong (purple). Best-fit functions with Equation (3) are shown with color lines and the parameter values are listed in Table 1.

**References**

Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481

Behroozi, P. S., Wechsler, R. H., & Conroy, C. 2013, ApJ, 770, 205

Bergeron, J., & Boissé, P. 1991, A&A, 243, 344

Chen, H.-W., Helsby, J. E., Gauthier, J.-R., et al. 2010, ApJ, 714, 1521

Churchill, C. W., Vogt, S. S., & Charlton, J. C. 2003, AJ, 125, 98

Crighton, N. H. M., Hennawi, J. F., Simcoe, R. A., et al. 2015, MNRAS, 446, 18

Draine, B. T. 2011, in Physics of the Interstellar and Intergalactic Medium, ed. B. T. Draine (Princeton, NJ: Princeton Univ. Press)

Ferland, G. J., Porter, R. L., van Hoof, P. A. M., et al. 2013, RMxAA, 49, 137

Fukugita, M., & Ménard, B. 2012, ApJ, 754, 116

Fukugita, M., & Ménard, B. 2015, ApJ, 799, 195

Haardt, F., & Madau, 2001, in Clusters of Galaxies and the High Redshift Universe Observed in X-rays, ed. D. M. Neumann & J. T. T. Van (Saclay: CEA), 64

Haardt, F., & Madau, 2012, ApJ, 746, 125

Lan, T.-W., Ménard, B., & Zhu, G. 2014, ApJ, 795, 31

Ledoux, C., Noterdaeme, P., Petitjean, P., & Srianand, R. 2015, A&A, 580, A8

Matejek, M. S., Simcoe, R. A., Cooksey, K. L., & Seyffert, E. N. 2013, ApJ, 764, 9

Ménard, B., & Chelouche, D. 2009, MNRAS, 393, 808

Ménard, B., & Fukugita, M. 2012, ApJ, 754, 116

Ménard, B., Nestor, D., Turnshek, D., et al. 2008, MNRAS, 385, 1053

Morton, D. C. 2003, ApJS, 149, 205

Nielsen, N. M., Churchill, C. W., & Kacprzak, G. G. 2013, ApJ, 776, 115

Päris, I., Petitjean, P., Ross, N. P., et al. 2017, A&A, 597, A79

Pettini, M., Smith, L. J., Hunstead, R. W., & King, D. L. 1994, ApJ, 426, 79

Prochaska, J. X., & Hennawi, J. F. 2009, ApJ, 690, 1558

Prochaska, J. X., Werk, J. K., Worseck, G., et al. 2017, ApJ, 837, 169

Quirist, S., Péroux, C., Zafar, T., et al. 2016, MNRAS, 458, 4074

Rafelski, M., Wolfe, A. M., Prochaska, J. X., Neeleman, M., & Mendez, A. J. 2012, ApJ, 755, 89

Rao, S. M., Turnshek, D. A., & Nestor, D. B. 2006, ApJ, 636, 610

Rao, S. M., Turnshek, D. A., Sardane, G. M., & Monier, E. M. 2017, MNRAS, 471, 3428

Rauch, M., Sargent, W. L. W., & Barlow, T. A. 1999, ApJ, 515, 500

Rigby, J. R., Charlton, J. C., & Churchill, C. W. 2002, ApJ, 565, 743

Schneider, D. P., Richards, G. T., Hall, P. B., et al. 2010, AJ, 139, 2360

Som, D., Kulkarni, V. P., Meiring, J. M., et al. 2015, ApJ, 806, 25

Steidel, C. C., Dickinson, M., & Persson, S. E. 1994, ApJL, 437, L75

van Steenberg, M. E., & Shull, J. M. 1988, ApJ, 330, 942

Welty, D. E., Lauroesch, J. T., Blades, J. C., Hobbs, L. M., & York, D. G. 2001, ApJL, 554, L75

Wild, V., Hewett, P. C., & Pettini, M. 2006, MNRAS, 367, 211

York, D. G., Adelman, J., Anderson, J. E., Jr., et al. 2000, AJ, 120, 1579

York, D. G., Khare, P., & Shull, J. M. 2001, ApJL, 554, L75

Zhu, G., & Ménard, B. 2013, ApJ, 770, 130