KECK AND VLT OBSERVATIONS OF SUPER-DAMPED Lyα ABSORBERS AT z~2–2.5: CONSTRAINTS ON CHEMICAL COMPOSITIONS AND PHYSICAL CONDITIONS*

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ABSTRACT

We report Keck/Echellette Spectrograph and Imager and Very Large Telescope/Ultraviolet-Visual Echelle Spectrograph observations of three super-damped Lyα quasar absorbers with H i column densities $\log N_{\text{HI}} \geq 21.7$ at redshifts $2 \lesssim z \lesssim 2.5$. All three absorbers show similar metallicities ($\sim-1.3$ to $-1.5$ dex), and dust depletion of Fe, Ni, and Mn. Two of the absorbers show supersolar [S/Zn] and [Si/Zn]. We combine our results with those for other damped Lyα absorbers (DLAs) to examine trends between $N_{\text{HI}}$, metallicity, and dust depletion. A larger fraction of the super-DLAs lie close to or above the line $[\text{X}/\text{H}] = 20.59 - \log N_{\text{HI}}$ in the metallicity versus $N_{\text{HI}}$ plot, compared to the less gas-rich DLAs, suggesting that super-DLAs are more likely to be rich in molecules. Unfortunately, our data for Q0230−0334 and Q0743+1421 do not cover H2 absorption lines. For Q1418+0718, some H2 lines are covered, but not detected. CO is not detected in any of our absorbers. For DLAs with $\log N_{\text{HI}}, < 21.7$, we confirm strong correlation between metallicity and Fe depletion, and find a correlation between metallicity and Si depletion. For super-DLAs, these correlations are weaker or absent. The absorbers toward Q0230−0334 and Q1418+0718 show potential detections of weak Lyα emission, implying star formation rates of ~1.6 and ~0.7 $M_\odot$ yr$^{-1}$, respectively (ignoring dust extinction). Upper limits on the electron densities from C ii/C ii or Si ii/Si ii are low, but are higher than the median values in less gas-rich DLAs. Finally, systems with $\log N_{\text{HI}}, > 21.7$ may have somewhat narrower velocity dispersions $\Delta v_{90}$ than the less gas-rich DLAs, and may arise in cooler and/or less turbulent gas.

Key words: galaxies: abundances – quasars: absorption lines

1. INTRODUCTION

Galaxies such as the Milky Way contain a large fraction of their present-day mass in stars. However, their chemically less-enriched analogs at higher redshifts are more dominated by gas. How galaxies exchange gas with their surroundings and how they progressively convert this gas into stars and enrich it chemically remain as some of the core questions in astrophysics.

Star formation is well-known to be associated with cold, neutral gas. Indeed, the star formation rate (SFR) is known to be strongly correlated with the surface density of neutral gas, as per the Kennicutt–Schmidt law (e.g., Schmidt 1959; Kennicutt 1998). The most gas-rich galaxies thus offer an opportunity to study the most vigorously star-forming regions. Furthermore, such regions can potentially allow a look at interesting chemical enrichment processes in young galaxies.

A powerful technique to study gas-rich galaxies is to search for their strong absorption signatures in the light of background sources such as quasars or gamma-ray bursts (GRBs). Damped Lyα absorbers (DLAs) with neutral hydrogen column densities $N_{\text{HI}} \geq 2 \times 10^{20}$ cm$^{-2}$ and sub-DLAs with $10^{19} < N_{\text{HI}} < 2 \times 10^{20}$ cm$^{-2}$ dominate the mass density of neutral gas in the universe (e.g., Péroux et al. 2005; Prochaska & Wolfe 2009).

Noterdaeme et al. 2012b; Zafar et al. 2013), and may be the progenitors of galaxy disks or halos. Absorbers with $\log N_{\text{HI}} \geq 21.7$ have been detected in many GRBs (>60% of GRB DLAs), but are very rare (~0.5%) among quasar DLAs. Despite their small numbers, these extremely gas-rich systems may contribute ~10% of the comoving neutral gas density (Noterdaeme et al. 2012b, 2014). About 100 such “super-DLAs” have been discovered in the Sloan Digital Sky Survey (SDSS) spectra. Study of these extremely gas-rich systems offers an excellent opportunity to understand star formation and chemical enrichment in young, gas-rich galaxies. Such studies are especially important at redshifts 2 < z < 3, corresponding to the epoch of peak global star formation activity (e.g., Madau et al. 1998; Bouwens et al. 2011).

The first detailed studies of an intervening quasar super-DLA were those of the z ≈ 2.2 absorber toward SDSS J1135-0010, carried out by Kulkarni et al. (2012) and Noterdaeme et al. (2012a) using the Very Large Telescope (VLT) Ultraviolet-Visual Echelle Spectrograph (UVES) and X-shooter. This super-DLA is fairly enriched, with $[\text{Zn}/\text{H}] = -1.06 \pm 0.10$, $[\text{Si}/\text{H}] = -1.10 \pm 0.10$, $[\text{Cr}/\text{H}] = -1.55 \pm 0.10$, $[\text{Ni}/\text{H}] = -1.60 \pm 0.10$, $[\text{Fe}/\text{H}] = -1.76 \pm 0.10$, $[\text{Ti}/\text{H}] = -1.69 \pm 0.11$, $[\text{P}/\text{H}] = -0.93 \pm 0.23$, and $[\text{Cu}/\text{H}] = -0.75 \pm 0.14$. Furthermore, it shows strong Lyα emission near the bottom of the DLA trough and other nebular emission lines, implying a fairly high SFR of ~25 $M_\odot$ yr$^{-1}$. The Lyα emission shows two distinct peaks (each >7σ), possibly suggesting outflowing gas (Noterdaeme et al. 2012a).

In fact, stacked SDSS spectra of quasars with Super-DLA absorbers (shifted to the rest frame of the absorbers) show a statistical detection of Lyα emission at the bottom of the
DLA trough, suggesting close association with Lyα emitters (Noterdaeme et al. 2014) and small impact parameter (so that the emission falls in the fiber). There are also indications that at least some super-DLAs may be rich in molecular gas (e.g., Guimaraes et al. 2012; Noterdaeme et al. 2015a). Such quasar super-DLAs may resemble the DLAs arising in GRB hosts (e.g., Guimaraes et al. 2012). Indeed, GRB DLAs possibly arise in inner parts of galaxies, while most (less gas-rich) quasar DLAs probably arise in outer parts.

In principle, large H i column densities could also be associated with large sizes and hence large masses of absorbing galaxies. It is therefore also interesting to examine whether super-DLAs show larger velocity dispersions, using measurements of metal absorption line profiles.

With the goal of further understanding the unique properties of this rare class of galaxies, we have recently started obtaining follow-up spectroscopy of quasars that show super-DLA absorbers in SDSS spectra. Here we report a study of three super-DLAs at $2 \lesssim z \lesssim 2.5$, based on our observations obtained with Keck and VLT.

This paper is organized as follows: Section 2 describes the observations, data reduction, and absorption line measurements. Section 3 presents the results of profile fitting and column density measurements. Section 4 discusses the results and compares the chemical compositions and physical properties of super-DLAs with those for other DLAs presented in the literature. Section 5 summarizes our main conclusions.

## 2. Observations and Data Reduction

Table 1 lists the targets. These quasars were selected for our study because their SDSS spectra show DLAs with log $N_{\text{HI}} \gtrsim 21.7$ and the presence of several metal lines (Noterdaeme et al. 2014). We obtained follow-up Keck Echelle Spectrograph and Imager (ESI) or VLT UVES spectra of these quasars to achieve higher spectral resolution than the SDSS data, which is essential for our goal of accurate element abundance measurements.

### 2.1. Keck ESI Observations

The quasars Q0230$-0334$ and Q0743$+1421$ were observed in classical mode with the Keck ESI (Sheinis et al. 2002) on 2013 November 7–8 under NOAO program 2013B-0525 (PI: V. Kulkarni). Severe weather problems resulted in a loss of 1.8 nights out of the two nights awarded, allowing us to obtain only one exposure for Q0230$-0334$ and three exposures for Q0743$+1421$.

The ESI spectra were reduced and extracted using ESIRedux, an IDL-based reduction package written by J. X. Prochaska. The extracted spectra from individual orders were split on average into three pieces (typically ~100–400 Å wide), and these pieces were continuum-fitted using the IRAF “CONTINUUM” task. To fit the continuum in each piece, we tried both cubic spline and Legendre polynomials, typically of an order between 3–5, and used the function that provided the best fit as judged from the rms of the residuals. For the absorber toward J0743$+1241$, the continuum-normalized pieces from the three exposures were combined into a single piece for each wavelength range using the IRAF “SCOMBINE” task.

### 2.2. VLT UVES Observations

The quasar Q1418$+0718$ was observed with UVES (Dekker et al. 2000) on VLT under program 093.A-0422 (PI: C. Péroux) in Service Mode on 2014 May 26, June 18, and July 24. The object was observed using a combined 437 + 760 nm setting with three different observations with exposure times lasting 5400 s each. The data were reduced using the most recent version of the UVES pipeline in MIDAS (uves/5.4.3). Master bias and flat images were constructed using calibration frames taken closest in time to the science frames. The science frames were extracted with the “optimal” option. The resulting spectra were combined, weighting each spectrum by the signal-to-noise ratio (S/N) and correcting to the vacuum heliocentric reference. The quasar continuum was fitted using the IRAF CONTINUUM task on regions of reasonable size (typically ~100–300 Å wide). Cubic spline, Legendre, and Chebyshev polynomials of various orders were tried, and usually the cubic spline fits were found to be the best.

### 2.3. Absorption Line Measurements

Column densities were determined by Voigt profile fitting using the program VPFIT4 version 10.0. Figures 1–3 show the Voigt profile fits to the H i Lyα lines for other DLAs toward Q0230$-0334$, Q0743$+1421$, and Q1418$+0718$, respectively. For Q0743$+1241$, the ESI spectra did not cover the Ly-alpha absorption line of the super-DLA absorber; therefore, the relevant region of the SDSS Data Release 12 (DR 12) Baryon Oscillation Spectroscopic Survey (BOSS) spectra was fitted to measure the $N_{\text{HI}}$ for this super-DLA, using a seventh-order Chebyshev function for continuum fitting (Figure 2). Figures 4–5, 6–8, and 9 correspondingly show the profile fits to key metal lines in these systems.

The total column densities were obtained by summing over all the velocity components. These values were checked independently using the apparent optical depth method (AOD; see Savage & Sembach 1991) for unsaturated, unblended lines. For consistency with past studies (which we compare to our results in Section 4 below), we have adopted oscillator strengths from Morton (2003). We note, however, that more recent oscillator strength determinations exist for some elements (e.g., Kisielius et al. 2014, 2015), and should be uniformly applied to all future element abundance studies in DLA/sub-DLAs. (For the key elements S and Zn, these revised oscillator strengths would result in DLA abundances higher by

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Table 1

| Quasar     | R.A., Dec.(J2000) | $z_{\text{em}}$ | $z_{\text{abs}}$ | Instrument | Integration Time |
|------------|------------------|----------------|------------------|------------|------------------|
| Q0230$-0334$ | 02:30:11.30$-03:34:50.2$ | 2.872 | 2.5036 | Keck/ESI | 2100 s x 1 |
| Q0743$+1421$ | 07:43:44.26$+14:21:34.9$ | 2.281 | 2.045 | Keck/ESI | 1800 s x 2 + 1300 s |
| Q1418$+0718$ | 14:18:01.86$+07:18:43.6$ | 2.572 | 2.3920 | VLT/UVES | 5400 s x 3 |

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4 http://www.ast.cam.ac.uk/rfc/VPFIT.htm
Figure 1. H I Lyα absorption feature in our ESI data for the $z = 2.5036$ absorber toward J0230-0334. The continuum-normalized flux is shown in black, while the 1σ error array in the normalized flux is shown in red. The solid green curve represents the best-fitting Voigt profile corresponding to log $N_{H I} = 21.74$ and the dashed blue curves denote the profiles corresponding to estimated ±1σ deviations (±0.1 dex) from the best-fitting $N_{H I}$ value. The horizontal dashed red line denotes the continuum level. The vertical dotted black line denotes the center of the Lyα line.

Figure 2. Same as Figure 1, but for the $z_{abs} = 2.045$ super-DLA toward Q0743+1421. The solid green and dashed blue profiles correspond to log $N_{H I} = 21.9 ± 0.1$.

Figure 3. Same as Figure 1, but for the $z = 2.392$ super-DLA toward Q1418+0718. The solid green and dashed blue profiles correspond to log $N_{H I} = 21.7 ± 0.1$.

3. RESULTS OF PROFILE FITTING AND COLUMN DENSITY MEASUREMENTS

Tables 2 and 3 list the measurements of metal column densities for the absorber toward Q0230−0334. Tables 6 and 7 list the metal column density measurements for the absorber toward Q0743+1421, and Table 10 lists the metal column density measurements for the absorber toward Q1418+0718. Tables 4, 8, and 11 give the total column densities (summed over individual velocity components) derived from the profile fits, along with the AOD estimates, if available. Tables 5, 9, and 12 list the corresponding element abundances, calculated using the total metal column densities along with the H I column density, and using the solar abundances from Asplund et al. (2009). No ionization corrections were calculated, since the corrections are negligible at such high H I column densities.

4. DISCUSSION

4.1. Element Abundances and Dust Depletions

The element Zn is often used as a metallicity indicator in DLAs (e.g., Pettini et al. 1990, 1997). While there are several possible nucleosynthetic channels for Zn production (see, e.g., Matteucci et al. 1993; Kobayashi et al. 2006) making the nucleosynthetic origin of Zn unclear, on average Zn is observed to track Fe in the Milky Way halo stars, with [Zn/Fe] ~ 0.0 for $-2.0 < [\text{Fe/H}] < 0.0$ and [Zn/Fe] ~ 0.1 dex for $-2.7 < [\text{Fe/H}] < -2.0$ (e.g., Mishenina et al. 2002; Nissen et al. 2004, 2007). Furthermore, Zn is relatively undepleted on interstellar dust grains (e.g., Jenkins 2009); thus the gas-phase abundance of Zn is a good indicator of the total Zn abundance, without the need for uncertain dust depletion corrections. By contrast, elements such as Fe, Cr, and Ni are significantly depleted on interstellar dust grains in the Milky Way. Therefore, their abundance relative to Zn gives an indication of dust depletion.

All three super-DLAs in our sample show Zn abundances in the narrow range of $-1.35$ to $-1.47$ dex. Furthermore, we see [Fe/Zn] of $-0.30$, $-0.59$, and $-0.48$ dex, respectively, in the super-DLAs toward Q0230−0334, Q0743+1421, and Q1418+0718. Likewise, [Ni/Zn] in the three systems is observed to be $-0.29$, $-0.59$, and $-0.59$ dex. Mn is even less abundant relative to Zn, with [Mn/Zn] of $-0.39$, $-0.74$, and $-0.81$, respectively, in the absorbers toward Q0230−0334, Q0743+1421, and Q1418+0718. Cr appears to be weakly depleted in the absorbers toward Q0230−0334 and Q1418+0718, with [Cr/Zn] of $0.0 ± 0.11$, and $-0.13 ± 0.22$, respectively. The absorber toward Q0743+1421 shows a higher Cr depletion, with [Cr/Zn] of $-0.41 ± 0.04$. The low depletion of Cr seems surprising for the absorber toward Q0230−0334.

Another potentially interesting feature of the relative abundance patterns is that in two out of the three super-DLAs studied here, Si is observed to be more abundant relative to Zn than in the Sun, with [Si/Zn] of $0.25 ± 0.10$ and $0.23 ± 0.22$ dex relative to the Sun. S, which shows nearly zero depletion in the Galactic interstellar medium (ISM; e.g., Savage & Sembach 1996), is a better indicator of the abundance of the α elements than Si (which is depleted by $\sim 0.3– 0.4$ dex even in the warm Galactic ISM, e.g., Savage & Sembach 1996; Jenkins 2009). It is therefore interesting to note that, in both

0.04 dex and lower by 0.10 dex, respectively.) Solar system abundances were adopted from Asplund et al. (2009).
systems for which we have S measurements, S is also more abundant relative to Zn than in the Sun. In the super-DLAs toward Q0230−0334 and Q1418+0718, the S/Zn ratio is 2.85 dex and 3.05 dex, respectively. Compared to the solar ratios, the S/Zn ratios in these super-DLAs are higher by 0.29 ± 0.20 and 0.49 ± 0.27 dex, respectively. S/Si is somewhat higher than solar: the S/Si ratios in the super-DLAs toward Q0230−0334 and Q1418+0718 are −0.35 dex and 0.13 dex, respectively, i.e., higher by 0.04 ± 0.12 dex and 0.52 ± 0.17 dex, respectively, than in the Sun. Of course, higher S/N observations are clearly needed to obtain smaller uncertainties in these relative abundance measurements. If Zn tracks Fe-peak elements in these absorbers, this could suggest that these systems have enhanced α/Fe-group abundances (as seen, e.g., in the halo stars of the Milky Way), along with some Si depletion. We note, however, that Nissen & Schuster (2011) found [Zn/Fe] ∼ −0.15 dex for a subset of halo stars with high [α/Fe], and [Zn/Fe] ∼ 0.0 dex for halo stars with low [α/Fe], and have suggested that the behavior of Zn is similar to that of α elements. However, in the absence of knowledge about the intrinsic α/Fe ratio in DLAs (which is complicated by the higher depletion of Fe), it is not clear whether DLAs are similar to the high-α or low-α halo stars. The large [S/Zn] and [Si/Zn] values in the super-DLAs toward Q0230−0334 and Q1418+0718 suggest that Zn does not behave like an α element in these absorbers. In any case, the large [S/Fe] values (0.59 and 0.97 dex) in the super-DLAs toward Q0230−0334 and Q1418+0718 also suggest that they may show α-enhancement (along with some dust depletion).

4.2. Search for Rare Metals

Super-DLAs offer an excellent opportunity to study abundances of rare elements. The super-DLA toward Q1135−0010 showed the first detection of Cu in a quasar DLA, and in fact, Cu/Zn exceeding that in the Sun, [Cu/Zn] ∼ 0.31 ± 0.10 (Kulkarni et al. 2012). Such a level of [Cu/Zn] is surprising, given that Cu is depleted compared to Zn in the Galactic ISM (e.g., [Cu/Zn] ∼ −0.7 dex in the warm neutral medium (WNM) and ∼ −0.9 dex in the cold neutral medium (CNM; Jenkins 2009). Observations of such rare elements can offer additional constraints on nucleosynthetic processes in the underlying galaxies. For example, V and Co are believed to be produced mainly in explosive Si burning in supernovae (SNe)}
II and to a smaller extent in SNe Ia (e.g., Woosley & Weaver 1995; Bravo & Martinez-Pinedo 2012; Battistini & Bensby 2015).

For the super-DLAs toward Q0230−0334, Q0743+1421, and Q1418+0718, we searched the spectra for absorption lines of rare elements such as B, V, Co, Cu, Ge, and Ga, but no lines from these elements were detected. The 3σ upper limits on the column densities of these elements are listed under the “AOD” column in Tables 4, 8, 11, and the corresponding abundance limits are included in Tables 5, 9, 12. The absorber toward Q0230−0334 shows underabundant Cu, with $[\text{Cu/}Zn] < −0.25$; for the absorbers toward Q0743+1421 and Q1418...
+0718, the limits on Cu are less constraining with [Cu/Zn] < 0.21 and < 0.32, respectively. Both absorbers for which we have Co measurements show [Co/Zn] < −0.15. Higher S/N observations are necessary to obtain more definitive abundances of these rare elements.

4.3. Comparison with Other DLAs

We now compare some of the key properties of the super-DLAs with those of other DLAs. (Throughout this discussion, we refer to the other DLAs with 20.3 ≤ log \( N_{\text{HI}} \) ≤ 21.7 as just “DLAs” or “moderate DLAs”). To construct the super-DLA...
sample, we combine our results with those for 11 other super-
DLAs with \( z_{\text{abs}} < z_{\text{em}} \), that have element abundance determina-
tions based on moderate- or high-resolution spectroscopy
(typically \( R > 6000 \)). These other super-DLAs were reported
by Prochaska et al. (2003), Heinmuller et al. (2006),
Noterdaeme et al. (2007, 2008, 2015b), Kulkarni et al.
(2012), Guimaraes et al. (2012), Ellison et al. (2012), and
Berg et al. (2015).

Observations show a deficit of the general population of
DLAs with high \( N_{\text{HI}} \), and high metallicity. Boissé et al. (1998)
suggested that this deficit could arise from a dust selection effect:
high-\( N_{\text{HI}} \), high-metallicity systems could be more dusty,
and could obscure the background quasars more, thus
remaining systematically under-represented in the high-resolution
spectroscopic studies. On the other hand, the deficit of
high-\( N_{\text{HI}} \), high-metallicity DLAs may arise from hydrogen
becoming predominantly molecular, and hence undetectable in
\( \text{Ly}_\alpha \), above some \( N_{\text{HI}} \) threshold (that decreases with increasing
metallicity; Schaye 2001; Krumholz et al. 2009a).

Figure 10 compares the metallicity versus \( \text{H} I \) column density
data for DLAs and super-DLAs with detections of Zn or S
toward quasars and GRB afterglows. The red filled circles and
blue unfilled triangles show the measurements for quasar super-
DLAs from our work and those from the literature. The black
unfilled squares denote the measurements for other quasar
DLAs with \( \log N_{\text{HI}} < 21.7 \) (from many references such as
Prochaska et al. 2001, 2007; Ledoux et al. 2006; Meiring
et al. 2006; Péroux et al. 2006; Noterdaeme et al. 2008;
Rafelski et al. 2012, 2014; see Kulkarni et al. 2007, 2010, and
Som et al. 2015 for further details). The orange and green
diamonds denote the measurements for moderate DLAs and
super-DLAs toward GRB afterglows. The GRB data are from
Vreeswijk et al. (2004), Prochaska et al. (2007), Ledoux et al.
(2009), Savaglio et al. (2012), Cucchiara et al. (2015),
and references therein. The GRB DLAs and super-DLAs are at
the GRB redshifts and are thus associated with the GRB host
galaxies. We note that, while we have used the \( N_{\text{HI}} \) reported in
these studies for the GRB DLAs, the \( \text{HI} \) behind the GRB is not
sampled by the GRB DLA sightlines, since the GRB is located
within the host galaxy. Thus the true \( N_{\text{HI}} \) for the GRB
sightlines may be expected to be higher by a factor of two
(i.e., 0.3 dex) on average. The total metal columns along those
sightlines may also be proportionately larger, and so the
metallicities may not be that different. We show in solid
orange the line \( [X/\text{H}] = 20.59 - \log N_{\text{HI}} \), corresponding to the
"obscuration threshold" that was suggested by Boissé et al.
(1998) as a potential way to explain the deficit of DLAs with
large \( N_{\text{HI}} \) and high metallicity.

The short-dashed, dotted, dot-dashed, and long-dashed
lines in Figure 10 show the curves calculated by Krumholz
et al. (2009a) for “covering” fractions \( C_{\odot} = 0.01, 0.05, 0.5, \) and
1.0 for the cross-section of the spherical molecular

Figure 9. Same as Figure 4, but for key metal absorption lines in the \( z = 2.392 \) super-DLA toward Q1418+0718.
Table 2
Results of Voigt Profile Fitting for Lower Ions in the z = 2.5036 Absorber toward J0230-0334

| z                  | \(b_{\text{eff}}\) | \(\log N_{\text{Mg}}\) | \(\log N_{\text{Cu}}\) | \(\log N_{\text{Zn}}\) | \(\log N_{\text{Ni}}\) | \(\log N_{\text{Al}}\) |
|--------------------|---------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| 2.50167 ± 0.00002 | 7.6 ± 0.7           | ...                     | 13.86 ± 0.07            | ...                     | ...                     | ...                     |
| 2.50329 ± 0.00014 | 45.6 ± 6.3          | 12.61 ± 0.14            | 14.99 ± 0.15            | 12.13 ± 0.41            | 13.75 ± 0.14            | 13.38 ± 0.21            |
| 2.50388 ± 0.00002 | 22.1 ± 2.0          | 12.44 ± 0.22            | 15.45 ± 0.07            | 12.88 ± 0.07            | 14.18 ± 0.05            | 13.92 ± 0.07            |

Note. * \(b_{\text{eff}}\) denotes the effective Doppler \(b\) parameter in km s\(^{-1}\). Logarithmic column densities are in cm\(^{-2}\).

Table 3
Results of Voigt Profile Fitting for Higher Ions in the z = 2.5036 Absorber toward J0230-0334

| z                  | \(b_{\text{eff}}\) | \(\log N_{\text{C}}\) | \(\log N_{\text{Si}}\) |
|--------------------|---------------------|-------------------------|-------------------------|
| 2.50345 ± 0.00004 | 84.8 ± 2.8          | 14.53 ± 0.02            | 13.70 ± 0.04            |
| 2.50394 ± 0.00004 | 18.4 ± 9.1          | 13.12 ± 0.48            | 13.45 ± 0.08            |
| 2.50518 ± 0.00005 | 5.4 ± 1.8           | 13.70 ± 0.33            | ...                     |

Note. * \(b_{\text{eff}}\) denotes the effective Doppler \(b\) parameter in km s\(^{-1}\). Logarithmic column densities are in cm\(^{-2}\).

Table 4
Total Column Densities for the z = 2.5036 Absorber toward J0230-0334

| Ion | \(\log N_{H}^a\) (cm\(^{-2}\)) | \(\log N_{\text{Mg}}^a\) (cm\(^{-2}\)) |
|-----|-------------------------------|-------------------------------------|
| H I  | 21.74 ± 0.10                  | ...                                 |
| C IV | 14.60 ± 0.05                  | 14.59 ± 0.01                        |
| B II | ...                           | <11.78                              |
| Mg I | 12.83 ± 0.12                  | 12.85 ± 0.05                        |
| Al II| 13.19 ± 0.08                  | 13.14 ± 0.06                        |
| Si II| 16.15 ± 0.04                  | 15.96 ± 0.02                        |
| Si IV| ...                           | <12.85                              |
| S II | 15.80 ± 0.11                  | 15.72 ± 0.02                        |
| Ti II| ...                           | <12.83                              |
| V II | ...                           | <12.83                              |
| Cr II| 14.03 ± 0.07                  | ...                                 |
| Mn II| 13.43 ± 0.05                  | 13.36 ± 0.03                        |
| Fe II| 15.59 ± 0.06                  | 15.64 ± 0.03                        |
| Co II| ...                           | <13.23                              |
| Ni II| 14.32 ± 0.05                  | 14.32 ± 0.03                        |
| Cu II| ...                           | <12.33                              |
| Zn II| 12.95 ± 0.09                  | ...                                 |
| Ge II| ...                           | <12.82                              |

Note. * \(N_{H}\) and \(N_{\text{Mg}}\) values are in cm\(^{-2}\).

core of the cloud (surrounded by a shell of atomic gas). These \(c_{\text{H}_{2}}\) values correspond to molecular mass fractions \(f_{\text{H}_{2}} = M_{\text{H}_{2}}/M_{\text{total}} = [1 - (1 - c_{\text{H}_{2}})^{3}/\phi_{\text{mol}}]^{-1} = 0.010, 0.102, 0.845, and 1.0, respectively. The quantity \(\phi_{\text{mol}}\) is the ratio of molecular gas density to atomic gas density, and is about 10 (Krumholz et al. 2009b).

Several interesting facts emerge from Figure 10: (1) a much larger fraction of the quasar super-DLAs (~46%) lie on or above the “obscuration threshold,” while only ~9% of the moderate quasar DLAs lie on or above that threshold. About 77% of the quasar super-DLAs lie above or within 1σ of the obscuration threshold (including 2 of the 3 super-DLAs studied here), while only ~15% of the moderate quasar DLAs do so. For GRB absorbers, the super-DLA and DLA fractions above or within 1σ of the threshold are more comparable, ~75% and 60%, respectively. (We note that the fractions of GRB DLAs and super-DLAs above or within 1σ of the threshold would be larger if their \(N_{H}\) values are larger by a factor of ~2.) (2) In this sense, the quasar super-DLAs are more similar to the GRB absorbers than are the moderate quasar DLAs. Indeed, given that the GRB DLAs are believed to arise in star-forming regions within the main body of the galaxies (e.g., Pontzen et al. 2010), quasar super-DLAs are also likely to arise in quasar sightlines with small impact parameters to the absorber galaxies. (3) The \(H_{2}\) covering fraction is significant for several super-DLAs above the “obscuration threshold,” suggesting that they have higher molecular content than the moderate DLA population. This is consistent with the observations of \(H_{2}\) in five out of seven quasar super-DLAs by Noterdaeme et al. (2015a). Overall, it appears that the quasar super-DLAs are likely to arise more often in molecule-rich environments than the quasar moderate DLAs. (See Section 4.7 below for discussion of a search for molecular gas in the super-DLAs studied here.)

Figure 11 shows the abundance of Fe relative to X, plotted as a function of the metallicity \([X/H]\) (where X is taken
to be either Zn, or S if Zn is not available), for quasar DLAs and super-DLAs. We have omitted the super-DLA toward Q2140–0321, because it has very large uncertainties (>0.9 dex) in the [Zn/H] and [Fe/Zn] values, and no [S/H], [Fe/S] measurements are available. Figure 12 shows the abundance of Si relative to X, plotted as a function of the metallicity [X/H], for the DLAs and super-DLAs with Si and X detections (where, once again, X = Zn or S). Table 13 summarizes the statistics for the [Fe/X] versus [X/H] data and the [Si/X] versus [X/H] data for moderate DLAs and super-DLAs.

We first carried out bisector fits to the data in Figures 11 and 12. For the moderate DLAs, the intercepts for [Fe/X] and [Si/X] differ from each other at the ~5.0σ level. This difference probably arises from the stronger depletion of Fe than that of Si. The difference between the intercepts for the [Fe/X] and [Si/X] trends is less significant (~2.7σ) for super-DLAs; larger super-DLA samples are needed to determine whether this is an intrinsic difference or arises from the small sizes of the super-DLA samples. About 19% of the moderate DLA population and about 25% of the super-DLA population have [Si/X] > 0. This shows that the relative abundance patterns could be a combination of dust extinction and α-enhancement. We also note that the bisector fit slope and intercept for the super-DLA trends are consistent with those for the moderate DLAs, to within the uncertainties allowed by the present sample sizes. Again, larger super-DLA samples are needed for more definitive determinations of the metallicity versus depletion trends for super-DLAs.

Next, we examined how the metallicity and depletion correlate for the moderate DLAs and super-DLAs, using the Spearman rank-order correlation test. The results of this non-parametric test are also summarized in Table 13. An anti-correlation between [Fe/X] and [X/H] has been noted in previous works (e.g., Meiring et al. 2006, 2009; Noterdaeme

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**Table 6**

Results of Voigt Profile Fitting for Lower Ions in the \( z = 2.045 \) Absorber toward Q0743+1421

| \( \frac{b_d}{\text{eff}} \) | \( N_{\text{Al II}} \) | \( N_{\text{Al III}} \) | \( N_{\text{C II}} \) | \( N_{\text{C IV}} \) | \( N_{\text{Mg I}} \) | \( N_{\text{Mg II}} \) | \( N_{\text{Si II}} \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0.000003 1.799 ± 0.378 | >14.671 | 12.933 ± 0.0326 | >16.906 | >14.961 | 13.723 ± 0.0213 | 15.403 ± 0.0449 |

**Table 7**

Results of Voigt Profile Fitting for Higher Ions in the \( z = 2.045 \) Absorber toward Q0743+1421

| \( \frac{b_d}{\text{eff}} \) | \( N_{\text{C II}} \) | \( N_{\text{Si II}} \) |
|-----------------|-----------------|-----------------|
| 0.000003 1.799 ± 0.378 | 12.968 ± 0.0385 | >15.590 |

**Note.** \( * b_d \) denotes the effective Doppler \( b \) parameter in \( \text{km s}^{-1} \). Logarithmic column densities are in \( \text{cm}^{-2} \).

**Table 8**

Total Column Densities for the \( z = 2.045 \) Absorber toward Q0743+1421

| Ion | \( \log N_{\text{HI}} \) | \( \log N_{\text{AGRO}} \) |
|-----|-----------------|-----------------|
| H i | 21.90 ± 0.10 | ... |
| C i | ... | <13.08 |
| C ii | >16.91 | >14.82 |
| C ii' | >14.96 | >14.46 |
| C iv | 14.41 ± 0.07 | 14.21 ± 0.03 |
| B ii | ... | <12.26 |
| Mg i | 12.97 ± 0.04 | 12.71 ± 0.02 |
| Mg ii | >15.59 | >13.57 |
| Al ii | >14.67 | >13.35 |
| Al iii | 12.93 ± 0.03 | 12.82 ± 0.04 |
| Si ii | >16.08 | >15.76 |
| Si iii | ... | <13.01 |
| Si iv | 13.84 ± 0.06 | 13.76 ± 0.06 |
| V ii | ... | <13.79 |
| Cr iii | 13.72 ± 0.02 | 13.62 ± 0.02 |
| Mn ii | 13.18 ± 0.05 | 13.04 ± 0.03 |
| Fe ii | 15.40 ± 0.04 | 15.46 ± 0.06 |
| Co ii | ... | <13.67 |
| Ni ii | 14.12 ± 0.03 | 14.20 ± 0.04 |
| Cu ii | ... | <12.90 |
| Zn ii | 13.05 ± 0.03 | ... |
| Ga ii | ... | <12.07 |
| Ge ii | ... | <12.88 |

**Table 9**

Measured Element Abundances Relative to Solar for the \( z = 2.045 \) Absorber toward Q0743+1421

| Element | \( [X/H] \) |
|---------|-------------|
| C | >-3.51 |
| B | <0.3 |
| Mg | >-3.93 |
| Al | >-3.00 |
| Si | >-1.65 |
| V | <-1.0 |
| Cr | -1.82 ± 0.10 |
| Mn | -2.15 ± 0.11 |
| Fe | -2.00 ± 0.11 |
| Co | <1.2 |
| Ni | <2.00 ± 0.10 |
| Cu | <1.2 |
| Zn | -1.41 ± 0.10 |
| Ga | <0.9 |
| Ge | <0.7 |

**Note.** \( * \) Abundance estimates based on the dominant metal ionization state and H i.
Table 10

Results of Voigt Profile Fitting for Low Ions in the $z = 2.392$ Absorber toward Q1418+0718

| $z$       | $b_{\text{eff}}$ | $\log N_{\text{H}^\text{II}}$ | $\log N_{\text{O}^\text{II}}$ | $\log N_{\text{Si}^\text{II}}$ | $\log N_{\text{Ni}^\text{II}}$ | $\log N_{\text{Fe}^\text{II}}$ |
|-----------|------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| 2.39183 ± 0.000004 | 8.36 ± 0.27       | 13.65 ± 0.15                  | 17.72 ± 0.12                  | 15.94 ± 0.07                  |                               |                               |
| 2.39217 ± 0.000006 | 6.24 ± 0.54       | ...                           | 14.53 ± 0.19                  | 14.77 ± 0.13                  |                               |                               |
| $z$       | $b_{\text{eff}}$ | $\log N_{\text{N}^\text{II}}$ | $\log N_{\text{Ti}^\text{II}}$ | $\log N_{\text{Cr}^\text{II}}$ | $\log N_{\text{Fe}^\text{II}}$ |
| 2.39183 ± 0.000004 | 8.36 ± 0.27       | 15.84 ± 0.16                  | 15.61 ± 0.11                  | 12.96 ± 0.19                  |                               |
| 2.39217 ± 0.000006 | 6.24 ± 0.54       | ...                           | 12.96 ± 0.19                  | 12.93 ± 0.15                  |                               |

Note.

* $b_{\text{eff}}$ denotes the effective Doppler $b$ parameter in km s$^{-1}$. Logarithmic column densities are in cm$^{-2}$.

Table 11

Total Column Densities for the $z = 2.392$ Absorber toward Q1418+0718

| Ion   | $\log N_{\text{H}^\text{I}}$ (cm$^{-2}$) | $\log N_{\text{AOD}}$ (cm$^{-2}$) |
|-------|----------------------------------------|-----------------------------------|
| H I   | 21.70 ± 0.10                           | ...                               |
| B II  | ...                                    | <12.06                            |
| C I   | ...                                    | >13.84                            |
| C I*  | 13.65 ± 0.15                           | 13.66 ± 0.15                      |
| O I   | ...                                    | >15.13                            |
| Si II | 15.97 ± 0.07                           | 15.61 ± 0.11                      |
| Si I* | ...                                    | <12.00                            |
| Si IV | ...                                    | >13.20 ± 0.17                     |
| S II  | 15.84 ± 0.16                           | >15.17                            |
| Ti II | 12.65 ± 0.23                           | 12.96 ± 0.19                      |
| V II  | ...                                    | <12.55                            |
| Cr II | 13.74 ± 0.07                           | 13.79 ± 0.10                      |
| Mn II | 12.85 ± 0.08                           | 12.83 ± 0.12                      |
| Fe II | 15.25 ± 0.05                           | >14.82                            |
| Co II | ...                                    | <13.07                            |
| Ni II | 13.86 ± 0.06                           | 13.93 ± 0.15                      |
| Cu II | ...                                    | <12.98                            |
| Zn II | 12.79 ± 0.21                           | 12.93 ± 0.15                      |

Note.

* Abundance estimates based on the dominant metal ionization state and H I.

Table 12

Measured Element Abundances Relative to Solar for the $z = 2.392$ absorber toward Q1418+0718

| Element | [X/H]$^*$ |
|---------|-----------|
| C       | ≥−0.49    |
| B       | <−0.34    |
| O       | ≥−0.67    |
| Si      | ≤−1.24 ± 0.12 |
| S       | ≤−0.98 ± 0.19 |
| Ti      | ≤−2.00 ± 0.29 |
| V       | ≤−1.34    |
| Cr      | ≤−1.60 ± 0.12 |
| Mn      | ≤−2.28 ± 0.13 |
| Fe      | ≤−1.95 ± 0.11 |
| Co      | ≤−1.62    |
| Ni      | ≤−2.06 ± 0.11 |
| Cu      | ≤−1.15    |
| Zn      | ≤−1.47 ± 0.25 |

Note.

* Abundance estimates based on the dominant metal ionization state and H I.

Figure 10. Plot of metallicity (based on Zn or S absorption) vs. H I column density for quasar super-DLAs from this study and the literature, other quasar DLAs, and GRB DLAs/super-DLAs. Short-dashed, dotted, dot-dashed, and long-dashed curves show trends expected for molecular Hydrogen core “covering fractions” of 1.0, 0.5, 0.05, and 0.01, adopted from Krumholz et al. (2009a). The solid orange line shows the “obscuration threshold” of Boissé et al. (1998).

Figure 11. Plot of the depletion of Fe relative to Zn or S vs. the metallicity based on Zn or S, for quasar super-DLAs from this study and the literature, and for other quasar DLAs. The dashed line shows the bisector fit for the other quasar DLAs.
et al. 2008) and is indicative of increasing dust depletion with increasing metallicity. We confirm a strong anti-correlation for the moderate DLA population. For the smaller super-DLA sample, no correlation is seen. A [Si/X] versus [X/H] anti-correlation is also seen at a significant level for the moderate DLAs. A [Si/X] versus [X/H] may be present for the super-DLAs, but a larger super-DLA sample is needed to definitively determine whether such a correlation is indeed present, or whether it results from the small size of the current sample. It will also be interesting to determine [Fe/X] and [Si/X] in individual velocity components with higher resolution data to examine whether differences in the depletion pattern (such as those expected between cold and warm gas) are seen.

4.4. Search for Lyα Emission

The super-DLA toward Q1135+0010 shows strong emission lines of Lyα, H-α, and [O iii], implying SFR ~25 M_☉ yr^{-1} (Kulkarni et al. 2012; Noterdaeme et al. 2012a). This SFR level is much higher than that seen typically in the moderate DLA population. A higher SFR could also indicate a larger galaxy. The Lyα emission in the Q1135+0010 super-DLA shows symmetric double peaks, possibly arising in a starburst-driven outflow. In fact, stacked Super-DLA spectra show a statistical detection of Lyα emission at the bottom of the DLA trough, suggesting close association with Lyα emitters (Noterdaeme et al. 2014). Such quasar super-DLAs resemble the DLAs arising in GRB hosts (e.g., Guimaraes et al. 2012).

There is a hint of weak Lyα emission near the center of the DLA trough for the systems toward Q0230+0334 and Q1418+0718. For Q0230+0334, on resampling the ESI spectrum to 1.5 Å dispersion, we measure an integrated Lyα emission flux of (3.41 ± 1.03) × 10^{-17} erg s^{-1} cm^{-2}. The SDSS spectrum of the same source gives an integrated Lyα emission flux of (3.66 ± 1.50) × 10^{-17} erg s^{-1} cm^{-2}. For Q1418+0718, on resampling the UVES spectrum to 1.5 Å dispersion, we measure an integrated Lyα emission flux of (1.81 ± 0.80) × 10^{-17} erg s^{-1} cm^{-2}. These Lyα fluxes would correspond to SFRs of 1.55 ± 0.47 M_☉ yr^{-1} based on the ESI data (or 1.66 ± 0.47 M_☉ yr^{-1} based on the SDSS data) for the absorber toward Q0230+0334, assuming L_{Lyα}/L_∗ = 8.7 for case-B recombination, and adopting the Kennicutt (1998) relation between the SFR and H-α luminosity. The corresponding SFR estimate for the super-DLA toward Q1418+0718 is 0.74 ± 0.33 M_☉ yr^{-1}. We note that these estimates assume no correction for dust absorption or resonant scattering by neutral gas. The SFRs would be higher if dust extinction is present.

4.5. Constraints on Electron Densities

Fine structure lines, e.g., those of C ii or Si ii, allow constraints on the electron density, assuming equilibrium between collisional excitation and spontaneous radiative de-excitation (and assuming collisional excitation rate for electrons to dominate over that of H atoms and over other excitation sources such as UV pumping and pumping from the cosmic microwave background). While Si ii absorption has been detected in GRB DLAs, it is not common in quasar DLAs. Kulkarni et al. (2012) made the first detection of Si ii absorption in an intervening quasar DLA (in the super-DLA toward Q1135+0010). Unfortunately, no Si ii absorption is detected in any of the super-DLAs studied here. However, for the absorbers toward Q0234+0334 and Q0743+1421, we are able to constrain the electron density n_e using the upper limits on Si ii and the measurements or lower limits on Si ii. We use the Si ii collisional excitation rate C_{2} = 3.32 × 10^{-7} (T/10^{4})^{-0.5} \exp(-413.4/T) cm^{3} s^{-1} (see, e.g., Srianand & Petitjean 2000) and the Si ii spontaneous radiative de-excitation rate A_{21} = 2.13 × 10^{-3} s^{-1}. For the super-DLAs toward Q0234+0334 and Q0743+1421, we obtain n_e < 0.16 cm^{-3} and n_e < 0.28 cm^{-3}, respectively, for an assumed temperature T = 500 K, or n_e < 0.28 cm^{-3} and n_e < 0.48 cm^{-3}, respectively, for T = 7000 K. For the absorber toward Q0743+1421, no constraint on C ii/C ii could be obtained due to the saturation of C ii λ 1336 and C ii λ 1334. For the absorber toward Q0234+0334, C ii λ 1334 and C ii λ 1336 could not be measured due to severe blends with the Lyα forest.

The spectrum of Q1418+0718 shows a strong detection of C ii absorption, implying log N_{C ii} = 13.65. The C ii λ 1334 line in this absorber is saturated, and a well-constrained estimate of N_{C ii} could not be obtained from Voigt profile fitting. We therefore adopt the lower limit on N_{C ii} implied by the AOD method (log N_{C ii} ≥ 14.84). Combining these C ii and C ii measurements, we estimate the electron density to be n_e < 0.51 cm^{-3} for an assumed temperature T = 500 K or n_e < 1.03 cm^{-3} for T = 7000 K. However, Si ii is not detected in this absorber. Based on the upper limit on Si ii and the detection of Si ii, we obtain n_e < 0.035 cm^{-3} for T = 500 K or n_e < 0.061 cm^{-3} for T = 7000 K.

Higher S/N and higher resolution spectra are essential to obtain more definitive constraints on the electron densities in our super-DLAs. Shorter-wavelength observations covering C ii λ 1036.3 and C ii λ 1037.0 would also be useful to obtain additional constraints on the C ii and C ii column densities. We note, nevertheless, a couple of points. First, differences between n_e derived from different elements have been observed for the Galactic diffuse ISM (e.g., Welty et al. 2003). Welty et al. found a mean n_e ~ 0.14 ± 0.07 cm^{-3} for C, Na, and K. Furthermore, they found that n_e derived from the Ca ii/C ii ratio is often much greater than the value expected if most of the electrons come from the photoionization of C, and suggested that the ionization balance of heavy elements in the diffuse ISM is affected by additional processes besides photoionization and radiative recombination. Second, we also note that the median n_e in DLAs has been found to be 0.0044 ± 0.0028 cm^{-3} in a recent study (Neeleman et al. 2015).
2015). This is much lower than the electron density found for the super-DLA toward Q1315−0010 ($n_e = 0.53-0.91 \text{ cm}^{-3}$; Kulkarni et al. 2012). It would be interesting to investigate, with higher S/N, higher resolution data targeting fine-structure lines for a larger number of super-DLAs whether super-DLAs in general have higher electron densities than moderate DLAs. A higher electron density may indicate a higher degree of ionization, possibly arising from a higher degree of star formation compared to the moderate DLAs.

### 4.6. Cooling Rate and SFR Density

The C$'$ column densities can also be used to constrain the cooling rates and the SFR densities (Wolfe et al. 2003). For the super-DLA toward Q1418+0718, using the measurement of $N_{\text{CII}}$, we estimate the cooling rate $\dot{\nu} = N_{\text{CII}} h u_\lambda / n_e$, where $u_\lambda$ and $A_\lambda$ denote the frequency and the coefficient for spontaneous photon decay for the $^2P_{3/2}$ to $^2P_{1/2}$ transition (e.g., Pottasch et al. 1979). Using $A_{ul} = 2.29 \times 10^{-6}$, we estimate $\dot{\nu} = 2.57 \times 10^{-25}$ erg s$^{-1}$ per H atom. This is substantially lower than the cooling rate in the super-DLA toward Q1135−0010 (which was estimated by Kulkarni et al. 2012 to be in the range $2.6 \times 10^{-27} < \dot{\nu} < 1.2 \times 10^{-25}$ erg s$^{-1}$ per H atom), and suggests a lower SFR in the super-DLA toward Q1418+0718.

To estimate the SFR density, we use the fact that the Fe abundance, the Si abundance, and the cooling rate for the super-DLA toward Q1418+0718 are within 0.05–0.26 dex of those for the $z = 2.309$ DLA toward Q0100+13 from Wolfe et al. (2003). For the latter system, Wolfe et al. estimate log $\psi_{\text{Fe}} \sim -2.8 M_\odot$ yr$^{-1}$ kpc$^{-2}$ for the CNM and log $\psi_{\text{Si}} \sim -1.6 M_\odot$ yr$^{-1}$ kpc$^{-2}$ for the WNM. We therefore estimate the SFR density in the super-DLA toward Q1418+0718 to be approximately log $\psi_{\text{Fe}} \sim -3 M_\odot$ yr$^{-1}$ kpc$^{-2}$ for CNM or log $\psi_{\text{Si}} \sim -1.9 M_\odot$ yr$^{-1}$ kpc$^{-2}$ for WNM, roughly an order of magnitude lower than the SFR density range estimated for the super-DLA toward Q1135−0010 (Kulkarni et al. 2012). For comparison, we note that the Kennicutt (1998) relation $\psi_s = [2.5 \times 10^{-4}] \times [N_{\text{H}1}/1.26 \times 10^{20}]^{1.4}$ would imply log $\psi_{\text{Si}} \sim -1.4 M_\odot$ yr$^{-1}$ kpc$^{-2}$ for the super-DLA toward Q1418+0718. Measurements of C$'$ absorption in a larger sample of super-DLAs are essential to systematically compare their SFR densities with those in other DLAs and in nearby galaxies.

An SFR density of log $\psi_{\text{Si}} \sim -2.5 M_\odot$ yr$^{-1}$ kpc$^{-2}$, together with the SFR = 0.74 $M_\odot$ yr$^{-1}$ estimated above from the marginal Ly$\alpha$ emission, would imply the line of sight size of the absorber toward Q1418+0718 to be $\sim15$ kpc, if the star formation were spread uniformly within the absorber. This is much larger than the sizes observed ($\sim$ a few kiloparsecs) for star-forming galaxies at high redshift. However, the absorber could be considerably smaller in size depending on the clumpiness of the star formation and the relative WNM content. It would be very interesting to obtain integral field spectroscopic observations of super-DLAs, similar to those obtained for lower column density DLAs and sub-DLAs by Péroux et al. (2011, 2012, 2013) to study the spatial distribution of star formation and metallicity in these objects.

### 4.7. Search for Molecules

For Q0230−0334 and Q0743+1421, the wavelength coverage was not adequate to examine the Lyman or Werner band absorption lines of $H_2$. For Q1418+0718, the wavelength coverage includes $H_2$, Lyman band transitions in the range 1109–1152 Å in the absorber rest frame, but the S/N in this region is very low. No lines for the $H_2 J1–J7$ rotational levels were detected; the non-detections of the strongest transitions covered imply 3$\sigma$ upper limits of $N_{H_2 J1} < 15.55$, $N_{H_2 J2} < 15.66$, $N_{H_2 J3} < 15.77$, $N_{H_2 J4} < 15.84$, $N_{H_2 J5} < 15.16$, $N_{H_2 J6} < 15.23$, and $N_{H_2 J7} < 15.02$, respectively. The total of the $H_2 J1–J7$ column densities $log N_{H_2 J1–J7} < 16.40$ may suggest a low molecular content.

For all three of our absorbers, several lines of CO were covered, but not detected. From the non-detections of the strongest lines covered (near 1477 Å in the absorber rest frame), we estimate 3$\sigma$ upper limits of $log N_{\text{CO} J0} < 13.41$, $log N_{\text{CO} J1} < 13.71$, and $log N_{\text{CO} J2} < 13.71$ for the super-DLA toward Q0230−0334. For the absorber toward Q0743+1421, from the non-detection of the lines near 1477 and 1544 Å, we estimate 3$\sigma$ upper limits of $log N_{\text{CO} J3} < 13.56$, $log N_{\text{CO} J4} < 13.86$, $log N_{\text{CO} J5} < 13.86$, $log N_{\text{CO} J6} < 14.12$, $log N_{\text{CO} J7} < 14.12$, $log N_{\text{CO} J8} < 14.12$, and $log N_{\text{CO} J9} < 14.12$, and a total $log N_{\text{CO} J0–J9} < 14.85$. For the absorber toward Q1418+0718, we estimate 3$\sigma$ upper limits of $log N_{\text{CO} J0} < 13.68$, $log N_{\text{CO} J1} < 14.02$, $log N_{\text{CO} J2} < 13.98$, $log N_{\text{CO} J3} < 14.63$, $log N_{\text{CO} J4} < 14.63$, $log N_{\text{CO} J5} < 14.64$, and $log N_{\text{CO} J6} < 14.65$, from the non-detections of the strongest transitions covered (near 1368, 1419, and 1447 Å).

Noterdaeme et al. (2015a) reported strong H$_2$ detections with $log N_{H_2} < 17.1–20.1$ in five out of seven super-DLAs, and log $N_{H_2} < 14.6$ in the remaining two super-DLAs. Higher S/N and lower wavelength spectra of our super-DLAs are needed to obtain more definitive determinations of their H$_2$ and CO contents. If our super-DLAs indeed have low molecular contents despite having log $N_{H_1} > 21.7$, that would contrast with observations of the Galactic ISM, which shows a sharp increase in $H_2$ column densities at log $N_{H_1} > 20.7$ (e.g., Savage et al. 1977); however, low molecular contents would be

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**Table 13**

Summary of Depletion versus Metallicity Statistics

| Sample, $N_{H1}$ Range | Statistic                  | $[\text{Fe}/X]$ versus $[X/H]$ | $[\text{Si}/X]$ versus $[X/H]$ |
|------------------------|---------------------------|---------------------------------|---------------------------------|
| Moderate DLAs          | Bisector Fit Slope        | $-0.500 \pm 0.043$              | $-0.406 \pm 0.081$              |
| (20.3 $< log N_{H1} < 21.7$) | Bisector Fit Intercept    | $-1.06 \pm 0.059$              | $-0.514 \pm 0.091$              |
| Super-DLAs             | Bisector Fit Slope        | $-0.774 \pm 0.170$              | $-0.551 \pm 0.184$              |
| (log $N_{H1} > 21.7$)   | Bisector Fit Intercept    | $-1.52 \pm 0.24$               | $-0.677 \pm 0.208$              |
| Moderate DLAs          | Spearman $r_s$, $P$       | $-0.596, <1.0 \times 10^{-6}$   | $-0.404, 1.46 \times 10^{-3}$   |
| (20.3 $< log N_{H1} < 21.7$) | Spearman $r_s$, $P$       | $-0.441, 6.57 \times 10^{-2}$   | $-0.878, <5.0 \times 10^{-2}$   |
| Super-DLAs             | Spearman $r_s$, $P$       |                                  |                                 |
consistent with the low SFRs in our super-DLAs suggested by the marginal or weak detections of Lyα emission in the DLA troughs.

4.8. Gas Kinematics

A correlation between metallicity and gas velocity dispersion has been noted for DLAs (e.g., Ledoux et al. 2006; Meiring et al. 2007; Som et al. 2015). Such a correlation could indicate a mass–metallicity relation for the absorbing galaxies, if the gas velocity dispersion is a measure of the mass of the absorber. Alternatively, the velocity dispersion could reflect turbulent motions or outflows.

Figure 13 shows our measurements of the velocity dispersion $\Delta v_{90}$ for each of the three super-DLAs studied here. These measurements were made on well-detected, unsaturated lines such as Cr II $\lambda2056$ or Fe II $\lambda2250$. The velocity dispersions were found to be $\Delta v_{90} = 149.9 \text{ km s}^{-1}$, $67.9 \text{ km s}^{-1}$, and $31.8 \text{ km s}^{-1}$, respectively, for the absorbers toward Q0230−0334, Q0743+1421, and Q1418+0718. (While higher resolution spectra would give more reliable determinations of $\Delta v_{90}$ for the absorbers toward Q0230−0334 and Q0743+1421, we regard our values for these systems as reasonable approximations, given that they are quite distinct from each other and feasible at the spectral resolution of our data.) It is surprising that two of the three systems show such low velocity dispersions. A low velocity dispersion $\Delta v_{90} = 28 \text{ km s}^{-1}$ was also found for the $z_{\text{abs}} = 2.34$ super-DLA with log $N(HI) = 22.4$ toward Q2140−0321 (Noterdaeme et al. 2015b).

To compare the kinematics of regular DLAs and super-DLAs, we plot in Figure 14 the velocity dispersion versus the HI column density for DLAs and super-DLAs. Super-DLAs appear to have a somewhat smaller incidence of large velocity dispersions than other DLAs.

DLAs have $\Delta v_{90} > 90 \text{ km s}^{-1}$. Since the sample of super-DLAs with $\Delta v_{90}$ measurements is so small (10 systems), we also compare the samples with log $N(HI) < 21.5$ and log $N(HI) > 21.5$. The mean velocity dispersion is 125.6 km s$^{-1}$ for systems with log $N(HI) < 21.5$, and 79.2 km s$^{-1}$ for systems with log $N(HI) > 21.5$. A two-sample Kolmogorov–Smirnov test between DLAs with log $N(HI) < 21.5$ and those with log $N(HI) > 21.5$ gives $D = 0.309$ (D being the K-S statistic, i.e., the maximum absolute value of the difference between the cumulative distribution functions of $\Delta v_{90}$ for the two samples), with a probability of 0.815 that the two samples are not similar.

Figure 15 shows the metallicity versus log of the velocity dispersion for DLAs and super-DLAs. Once again, we exclude the super-DLA toward Q2140−0321, because it has a very large uncertainty ($>0.9$ dex) in [Zn/H] and no [S/H] measurement. The data for the moderate DLAs indeed show a significant correlation with a Spearman rank-order correlation coefficient $r_S = 0.655$ and a probability $P < 1 \times 10^{-5}$ of no correlation. The super-DLA data do not show a strong correlation ($r_S = 0.371, P = 1.46 \times 10^{-4}$), which could be a result of the fact that they occupy a narrow range in metallicity compared to moderate DLAs. The fact that most super-DLAs have metallicities below −1.0 dex may also explain the small
fraction of super-DLAs with high velocity dispersions. Measurements for more quasar super-DLAs are essential to determine whether there is a statistically significant difference between the velocity dispersion versus metallicity relations for quasar super-DLAs and other (moderate) quasar DLAs. If quasar super-DLAs indeed have smaller velocity dispersions on average than other quasar DLAs, this may argue against the possibility that the quasar super-DLAs arise in larger, more massive galaxies, if the velocity dispersion is a measure of the mass. Alternatively, it may suggest the presence of cooler or less turbulent gas in quasar super-DLAs than in other quasar DLAs. In this context, it is interesting to note that Arabsalmani et al. (2015) have recently examined the velocity dispersion versus metallicity relation for long-duration GRB host galaxies, and found it to be very similar to that for quasar DLAs. Moreover, they find weak evidence for the velocity dispersions being larger in GRB DLAs. It is therefore important to expand the velocity dispersion and metallicity samples for quasar super-DLAs in order to understand how they compare to GRB DLAs.

5. SUMMARY

We have analyzed Keck ESI and VLT UVES spectra of three super-DLA absorbers and measured abundances of a number of elements. All three absorbers show remarkably similar metallicities of \( \sim -1.3 \) to \( -1.5 \) dex and comparable, definitive depletion levels, as judged from [Fe/Zn] and [Ni/Zn]. Two of the absorbers show supersolar [S/Zn] and [Si/Zn]. Combining our measurements with those for other super-DLAs and moderate DLAs from the literature, we find that the correlation between Fe (as well as Si) depletion and metallicity is weaker for the super-DLAs than for the moderate DLAs. The offset between the best-fitting [Si/X] versus [X/H] and [Fe/X] versus [X/H] trends indicates the greater depletion of Fe compared to that of Si. Using the fine-structure lines of C II and Si II, we have constrained the electron densities in the absorbers. While we can only put upper limits on the electron densities, these limits are higher than the median electron densities in the general DLA population; this, together with comparable \( n_e \) values seen in a few other super-DLAs, could mean the presence of denser and/or more ionized gas in the super-DLAs. Using potential detections of weak Ly\( \alpha \) emission at the bottom of the DLA troughs, we estimate SFR in the absorbers toward Q0230–0334 and Q1418+0718 to be \( \sim 1.6 \) and \( \sim 0.7 \) M\(_{\odot}\) yr\(^{-1}\), respectively. For the absorber toward Q1418+0718, the C II measurement suggests an SFR density of \( \psi_\alpha \sim -3 \) M\(_{\odot}\) yr\(^{-1}\) kpc\(^{-2}\) for CNM or \( \psi_\alpha \sim -1.9 \) M\(_{\odot}\) yr\(^{-1}\) kpc\(^{-2}\) for WNM. Finally, measurements of the velocity spread \( \Delta v_{90} \) suggest that super-DLAs may have narrower velocity dispersions and may arise in cooler and/or less turbulent gas.

Our study has further demonstrated the potential of super-DLAs as unique laboratories to study the physical and chemical properties of potentially star-forming interstellar gas in distant galaxies. Observations of a larger super-DLA sample at higher S/N are essential to further understand the nature of these unique absorbers and how their underlying galaxies compare with those probed by the moderate DLAs, and also those probed by the GRB DLAs.

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