New Magellan Inamori Kyocera Echelle Observations of z < 1.5 sub-damped Lyman α systems

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ABSTRACT

The damped Lyman α (DLA) and sub-damped Lyman α (sub-DLA) systems seen in the spectra of quasi-stellar objects (QSOs) offer a unique way to study the interstellar medium (ISM) of high-redshift galaxies. In this paper, we report on new abundance determinations in a sample of 10 new systems, nine of the lesser studied sub-DLAs and one DLA along the line of sight to seven QSOs from spectra taken with the Magellan Inamori Kyocera Echelle spectrograph. Lines of Mg i, Mg ii, Al ii, Al iii, Ca ii, Mn ii, Fe ii and Zn ii were detected. Here, we give the column densities and equivalent widths of the observed absorption lines, as well as the abundances determined for these systems. Zn, a relatively undepleted element in the local ISM is detected in one system with a high metallicity of [Zn/H] = +0.27 ± 0.18. In another system, a high abundance based on the more depleted element Fe is seen with [Fe/H] = −0.37 ± 0.13, although Zn is not detected. The N_HI-weighted mean metallicity of these sub-DLA systems based on Fe is ⟨[Fe/H]⟩ = −0.76 ± 0.11, nearly ~0.7 dex higher (a factor of 5) than what is seen in DLAs in this redshift range. The relative abundance of [Mn/Fe] is also investigated. A clear trend is visible for these systems as well as systems from the literature, with [Mn/Fe] increasing with increasing metallicity in good agreement with Milky Way stellar abundances.

Key words: ISM: abundances – quasars: absorption lines.

1 INTRODUCTION

Quasar absorption line systems with strong Lyman α lines are often divided into two classes: damped Lyman α (DLAs, log N_HI ≥ 20.3) and sub-damped Lyman α (sub-DLA 19 < log N_HI < 20.3; Péroux et al. 2001) which contain a major fraction of the neutral gas in the Universe, while the majority of the baryons are thought to lie in the highly ionized and diffuse Lyman α forest clouds with log N_HI < 15 in intergalactic space (Petitjean et al. 1993; Danforth & Shull 2008). The lower threshold of log N_HI = 20.3 for classification of DLAs stems from previous 21-cm emission studies of nearby spirals, where the sensitivity-limited column density of log N_HI ~ 20.3 was seen to lie near the Holmberg radius (R_{26.5}) of the galaxy (Bosma 1981). None the less, the damping wings which can be used to accurately measure N_HI in these systems do begin the sub-DLA regime of log N_HI 19.0. With their high gas content, the DLA and sub-DLA systems are believed to be associated directly with galaxies at all redshifts in which they are seen.

Among the many elements often detected in quasi-stellar object (QSO) absorber systems including C, N, O, Mg, Si, S, Ca, Ti, Cr, Mn, Fe, Ni and Zn, Zn is the preferred tracer of the gas-phase enrichment from the different types of supernovae (SNe), as the α-capture elements, e.g. Si and O, are produced mainly in Type II
explosions while the iron peak elements are produced mainly by Type Ia SNe.

In previous studies, DLA systems have been the preferred systems for chemical abundance investigation owing to their high gas content (Prochaska & Wolfe 2002; Kulkarni et al. 2005; Meiring et al. 2006). Most DLAs, however, have been found to be metal poor, typically far below the solar level and below where models predict that the mean metallicity should be at the corresponding redshifts at which they are seen (e.g. Kulkarni et al. 2005 and references therein). The sub-DLA systems have until recently been largely ignored, with their contribution to the overall metal budget unknown. Evidence for the possibility of a non-negligible contribution from sub-DLAs to the metal budget came from Péroux et al. (2003), who noted that based on Fe ii lines the sub-DLA systems have faster evolution of the Fe abundance and higher abundances, on average, than DLA systems. This has also been validated by Kulkarni et al. (2007).

Galactic chemical evolution is a slow process, and long timescales must be examined to search for the signs of the gradual chemical enrichment that models predict (Pei, Fall & Hauser 1999; Cen et al. 2003). Although redshifts $z < 1.5$ span 70 per cent of the age of the Universe (using a concordance cosmology of $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$), few observations have been made of $z < 1.5$ sub-DLAs due to the lack of spectrographs with enough sensitivity in short wavelengths and the paucity of known sub-DLAs in this redshift range. With such a large fraction of the age of the Universe covered in the redshift regime, it is clearly important for understanding the nature of sub-DLA systems and galactic chemical evolution as well.

We have greatly increased the sample of sub-DLAs in past several years with our Very Large Telescope and Ultraviolet Visual Echelle Spectrograph (VLT UVES) and Magellan-II Magellan Inamori Kyocera Echelle (MIKE) spectra. In this paper, we report on 10 new systems observed with the MIKE spectrograph on the Magellan-II Clay telescope. The structure of this paper is as follows: In Section 2, we discuss details of our observations and data reduction techniques. Section 4 gives details on the individual objects in these new observations. Section 5 investigates the ratio of [Mn/Fe] in QSO absorbers. In Section 6, we discuss the abundances of these absorbers and give a brief discussion. We also provide an appendix at the end of this paper, showing plots of the ultraviolet (UV) spectra with the fits to the Lyman $\alpha$ lines, and tables containing the fit parameters for the individual systems.

## 2 OBSERVATIONS AND DATA REDUCTION

The observations presented here were made with the 6.5-m Magellan-II Clay telescope and the MIKE spectrograph (Bernstein et al. 2003) in 2007 September. This is a double-sided spectrograph with both a blue and a red camera, providing for simultaneous wavelength coverage from $\sim 3340$ to $\sim 9400$ Å. Targets were observed in multiple exposures of $1800–2700$ s each to minimize cosmic ray defects. The seeing was typically $< 1$ arcsec, averaging $\sim 0.7$ arcsec. All of the target QSOs were observed with the $1 \times 5$ arcsec$^2$ slit and the spectra were binned $2 \times 3$ (spatial by spectral) during readout. The resolving power of the MIKE spectrograph is $\sim 19 000$ and $\sim 25 000$ on the red and blue sides, respectively, with a 1-arcsec slit. Table 1 gives a summary of the observations.

These spectra were reduced using the MIKE pipeline reduction code in IDL developed by S. Burles, J. X. Prochaska and R. Bernstein. Wavelengths were calibrated using a Th–Ar comparison lamp taken after each exposure. The data were first bias subtracted from the overscan region and flat-fielded. The data were then sky subtracted and the spectral orders were extracted using the traces from flat-field images. These extracted spectra were then corrected for heliocentric velocities and converted to vacuum wavelengths. Each individual order was then combined in iraf using rejection parameters to reduce the effects of cosmic rays. These combined spectra were then normalized using a polynomial, typically of the order of 5 or less, or spline function to fit the continuum.

Our new observations consist of 10 absorbers, nine sub-DLAs and one DLA at $z_{abs} < 1.5$. See Meiring et al. (2008) for a discussion of our selection criteria. Throughout this paper, the QSO names are given in J2000 coordinates, except in Table 1 where the original name, based on J1950 coordinates, is also given if applicable (Hewitt & Burbidge 1987).

### 3 DETERMINATION OF COLUMN DENSITIES

Column densities were determined from profile fitting with the package fits6 (Welty, Hobbs & York 1991), which has evolved from the code by Vidal-Madjar et al. (1977). fits6 iteratively minimizes the $\chi^2$ value between the data and a theoretical Voigt profile that is convolved with the instrumental profile. The profile fit used multiple components, tailored to the individual system. For the central, core components, the effective Doppler parameters ($b_{eff}$) and radial velocities were determined from the weak and unsaturated lines, typically the Mg i $\lambda 2852$ line. For the weaker components at higher radial velocities, the $b_{eff}$ and component velocity values were determined from stronger transitions such as the Fe ii $\lambda\lambda3244, 2382$ and the Mg ii $\lambda\lambda 2796, 2803$ lines. A set of $b_{eff}$ and $v$ values were thus determined that reasonably fit all of the lines observed in the system. The same $b_{eff}$ values were used for all the species. The atomic data used in line identification and profile fitting are from Morton (2003).

#### Table 1. Summary of observations. $^a$ $m_v$, $^b$ $m_g$.

| QSO J2000 | Original or SDSS ID | RA Dec. | $m_v$ or $m_g$ | $v_{em}$ | $z_{abs}$ | $N_{HI}$ | Exposure Time (s) |
|-----------|---------------------|---------|----------------|--------|----------|---------|-----------------|
| Q0005+0524 Q0002+051 | 00:05:20.21 +05:24:10.8 | 16.9$^a$ | 1.899 | 0.8514 | 19.08 ± 0.04 | 3600 |
| Q0012−0122 Q0009−016 | 00:12:10.89 −01:22:07.5 | 18.1$^b$ | 1.998 | 1.3862 | 20.26 ± 0.03 | 5400 |
| Q0021+0104 J002127.88+010420.2 | 00:21:27.88 +01:04:20.1 | 18.6$^b$ | 1.829 | 1.3259 | 20.04 ± 0.11 | 8100 |
| ... ... | ... | ... | ... | ... | ... | ... | ... |
| Q0427−1302 Q0424−131 | 04:27:07.32 −13:02:53.6 | 17.5$^a$ | 2.166 | 1.4080 | 19.94 ± 0.04 | 12300 |
| Q1631+1156 Q1629+1120 | 16:31:45.24 +11:56:02.9 | 18.6$^b$ | 1.792 | 0.9004 | 19.70 ± 0.04 | 13500 |
| Q2051+190 Q2048+196 | 20:51:45.87 +19:50:04.3 | 18.5$^a$ | 2.367 | 1.1157 | 20.00 ± 0.15 | 13500 |
| Q2352−0028 SDSS J235253.51−002850.4 | 23:52:53.51 −00:28:51.3 | 18.5$^b$ | 1.628 | 0.8730 | 19.18 ± 0.09 | 13500 |
| ... ... | ... | ... | ... | ... | ... | ... | ... |

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In general, if a multiplet was observed, the lines were fit simultaneously up until convergence. For all of the systems, the Fe II λλ2344, 2374, 2382 lines were fit simultaneously to determine a set of column densities that fit the spectra reasonably well. Similarly, the Mg II λλ2796, 2803 lines were also fit together. Significant saturation of the Mg II λλ2796, 2803 and Al I λ1670 lines allowed for only lower limits to be placed on the column densities for these species. The Zn II λλ2026,137 line is blended with a line of Mg I λ2026,477. The Mg I contribution to the line was estimated using the Mg I λ2852 line, for which Ω is ~32 times that of the Mg I λ2026 line. The Zn II components were then allowed to vary while the Mg I components were held fixed. N_{Fe II} was determined by simultaneously fitting the Cr II λ2056 line and the blended Cr II + Zn II λ2062 line, where the contribution from Zn II was estimated from the Zn II + Mg I λ2062 line. See also Khare et al. (2004) and Meiring et al. (2007). Meiring et al. (2008) for a discussion of the profile fitting scheme. We adopt the standard notation:

\[ [X/H] = \log(N_X/N_{\odot}) - \log(N(H)/N_{\odot}) \]  

(1)

Solar system abundances have been adopted from Lodders (2003). As the Lyman α lines from which we can determine N_{HI} all lie in the UV, even when redshifted, space based UV spectra are necessary. Neutral Hydrogen column densities were determined from archived Hubble Space Telescope (HST) Space Telescope Imaging Spectrograph (STIS) and Faint Object Spectrograph (FOS) spectra available from the HST archives. These systems have previously had N_{HI} determined in Rao, Turnshek & Nestor (2006), although the plots for the sub-DLAs are not published. We give in the Appendix the plots of the Lyman α lines for these systems with the fits overlaid. In general, the fits from Rao et al. (2006) and our determinations agree quite well. However, for Q2051+1960 we have determined a different value of N_{HI} = 20.00 ± 0.15. In all other cases, we have used the values from Rao et al. (2006). Rest-frame equivalent widths (EWs) for the lines are given in Table 2, with 3σ upper limits based on the photon noise and continuum level given in cases without a detection.

### 4 NOTES ON INDIVIDUAL OBJECTS

#### 4.1 Q0005+0524 (zem = 1.899)

(System A, zabs = 0.8514). This fairly bright QSO has a weak sub-DLA system with log N_{HI} = 19.08 in the spectrum (Rao et al. 2006). Eight components were needed to fit the observed profiles. Lines of Mg I λ2852, Mg II λλ2796, 2803, Al I λλ1854, 1862 and Fe II λλ2344, 2374, 2382, 2586, 2600 were detected. No Zn II λλ2026, 2052 lines were detected with signal-to-noise ratio (S/N) ~ 50 in the region. An upper limit of [Zn/H] < −0.47 was placed based on the noise in the region. Based on Fe, the metallicity for this system is [Fe/H] = −0.76 ± 0.04. With the relatively low value of Fe II/Al III = +0.68 ± 0.04, there could be significant ionization in the system. Velocity plots of several lines are shown in Fig. 1.

#### 4.2 Q0012−0122 (zem = 1.998)

(System A, zabs = 1.3862). This system is a sub-DLA with log N_{HI} = 20.26 (Rao et al. 2006). Lines of Mg I λ2852, Mg II λλ2796, 2803, Al I λλ1670, Al II λλ1854, 1862, Si II λ1526 and Fe II λλ2344, 2374, 2382, 2586, 2600 were all detected. This system shows minimal α enhancement with [Si/Fe] = +0.12 ± 0.08. Depletions of both the Al II and Al I lines in this system show that Al III/Al II < −0.19. This system appears to be fairly metal poor. No Zn II λλ2026, 2062 lines were detected and an upper limit of

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**Table 2. Rest-frame EWs and 1σ errors of the observed absorption lines in mÅ.**

| QSO     | \(z_{abs}\) | Mg I | Mg II | Mg III | Al II | Al III | Al IV | Si II | Si III | Ca II | Ca III | Cr III |
|---------|-------------|------|-------|--------|-------|--------|-------|-------|--------|-------|--------|--------|
|         | 2576        | 2594 | 2606  | 2606   | 2786  | 2790   | 2803  | 2803  | 2803   | 2803  | 2803   | 2803   |
| Q0005+0524 | 0.8514     | <3   | <2    | <3     | <3    | <3     | <3    | <3    | <3     | <3    | <3     | <3     |
| Q0012−0122 | 1.3862     | <6   | <7    | <7     | <10   | <10    | <10   | <10   | <10    | <10   | <10    | <10    |
| Q0021+0104A | 1.3259     | <18  | <18   | <18    | <18   | <18    | <18   | <18   | <18    | <18   | <18    | <18    |
| Q0247−1302 | 1.4080     | <10  | <10   | <10    | <10   | <10    | <10   | <10   | <10    | <10   | <10    | <10    |
| Q1631+1156 | 0.9004     | <7   | <7    | <7     | <7    | <7     | <7    | <7    | <7     | <7    | <7     | <7     |
| Q2051+1950 | 1.1157     | 312  | 39    | 312    | 312   | 312    | 312   | 312   | 312    | 312   | 312    | 312    |
| Q2352−0028A | 0.8730     | <5   | <5    | <5     | <5    | <5     | <5    | <5    | <5     | <5    | <5     | <5     |
| Q2352−0028B | 1.0318     | 445  | 297   | 297    | 297   | 297    | 297   | 297   | 297    | 297   | 297    | 297    |
| Q2352−0028C | 1.2467     | 12   | 12    | 12     | 12    | 12     | 12    | 12    | 12     | 12    | 12     | 12     |

*a This line is a blend with Mg I λ2026, although the Mg I contribution is judged to be insignificant in all cases.

*b As this line is blended with the Cr II λ2062 line, this value represents the total EW of the line.

*Blended with another feature.”
Figure 1. Velocity plots for Q0005+0524. The solid green line indicates the theoretical profile fit to the spectrum and the dashed red line is the continuum level. The vertical dotted lines indicate the positions of the components that were used in the fit. In the cases of the Zn\textsc{ii} λλ2026, 2062 lines, the long dashed vertical lines indicate the positions of the components for Mg\textsc{i} (former case) and Cr\textsc{ii} (latter case). Areas shaded in grey are due to interloping absorption features or cosmetic defects.

\[ \text{[Zn/H]} < -1.34 \] was determined for this system. Based on Fe, the metallicity is \([\text{Fe/H}] = -1.49 \pm 0.02\). Velocity plots of several lines are shown in Fig. 2.

4.3 Q0021+0104 (\(z_{\text{em}} = 1.829\))

(System A: \(z_{\text{abs}} = 1.3259\)). This is a sub-DLA system with log \(N_{\text{HI}} = 20.04\) (Rao et al. 2006). We detect lines of Mg\textsc{i} λ2852, Mg\textsc{ii} λλ2796, 2803, Al\textsc{ii} λ1670, Al\textsc{iii} λλ1854, 1862, Si\textsc{ii} λλ2344, 2374, 2382, 2586, 2600. The Mn\textsc{ii} λ2576 was also possibly detected at a \(\sim 2\sigma\) level. The complex absorption profile required 13 components for an adequate fit. The Si\textsc{ii} λ1808 and Al\textsc{iii} λλ1854, 1862 lines fell in portions of the detector with serious cosmetic issues, so they could not be measured. No Zn\textsc{ii} lines are present in the spectra with S/N \(\sim 25\) in the region. The metallicity based on Zn is thus \([\text{Zn/H}] < -1.19\). Simultaneous fits to the Fe\textsc{ii} lines provide a measure of the Fe metallicity as \([\text{Fe/H}] = -0.82 \pm 0.11\). Due to the saturation of the Si\textsc{ii} λ1526 line, only a lower limit could be placed on the column density. Even with this lower column density, the system shows signs of \(\alpha\) enhancement with \([\text{Si/Fe}] > +0.14\). Velocity plots of several lines are shown in Fig. 3.

(System B: \(z_{\text{abs}} = 1.5756\)). This system is a DLA with log \(N_{\text{HI}} = 20.48\) (Rao et al. 2006). The complex velocity profile spanned \(\sim 600\ km\ s^{-1}\) in velocity space, and required 20 components in the fitting. Lines of Mg\textsc{i} λ2852, Mg\textsc{ii} λλ2796, 2803, Al\textsc{iii} λ1854, Si\textsc{ii} λλ1526 and Fe\textsc{ii} λλ1608, 2344, 2374, 2382, 2586, 2600 were detected. The Fe\textsc{ii} λλ1608, 2374 lines were weak enough that accurate column densities could be determined. This DLA has a metallicity from Fe of \([\text{Fe/H}] = -1.34 \pm 0.15\), typical of other DLA values in this redshift range. No Zn\textsc{ii} λλ2026, 2062 lines were detected in this system, and an upper limit of \([\text{Zn/H}] < -1.16\) was placed on the system. The Si\textsc{ii} λ1526 line was detected, although saturated. We derived a Si abundance for this system of \([\text{Si/H}] = -1.14\), which is consistent with the non-detection of the Si\textsc{ii} λ1808 line. This system shows weak \(\alpha\) enhancement with \([\text{Si/Fe}] = +0.20\), although this could also be due to differential dust depletion. Kinematically, this system has an interesting absorption profile with two strong clusters of components separated by \(\sim 100\ km\ s^{-1}\), possibly indicating a merging system. Velocity plots of several lines are shown in Fig. 4.

4.4 Q0427−1302 (\(z_{\text{em}} = 2.166\))

(System A: \(z_{\text{abs}} = 1.4080\)). This is a weak sub-DLA system with log \(N_{\text{HI}} = 19.04\) (Rao et al. 2006). Only three components were used in the fit, with the vast majority of the absorption in the \(v \sim 0\ km\ s^{-1}\) component. We detected lines of Mg\textsc{ii} λλ2796, 2803, Al\textsc{ii} λ1670, Si\textsc{ii} λ1526 and Fe\textsc{ii} λλ2344, 2374, 2382, 2586, 2600. This system is metal poor, with \([\text{Fe/H}] = -1.12 \pm 0.04\). No Zn\textsc{ii} λλ lines were detected with S/N \(\sim 55\) in the region, and an upper limit of \([\text{Zn/H}] < -0.58\) was placed on the system. The Al\textsc{iii} λλ1854, 1862 lines were covered but not detected. An upper limit was placed on

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Figure 2. Same as Fig. 1 but for Q0012+0122.

Figure 3. Same as Fig. 1 but for Q0021+0104A.
the Al III/Al II ratio of Al III/Al II < −1.14. This system also shows slight α enhancement with [Si/Fe] = +0.16 ± 0.03. Velocity plots of several lines are shown in Fig. 5.

4.5 Q1631+1156 (z_em = 1.792)

(System A: z_abs = 0.9004). This system is a sub-DLA with log N_HI = 19.70 (Rao et al. 2006). The Fe II λλ2344, 2374 lines were affected by a cosmetic defect in the chip, but the Fe II λλ2382, 2586, 2600 lines were detected. Other lines detected were Mg I λ2852, Mg II λλ2796, 2803 and Ca II 3934. The Zn II λλ2026, 2062 lines were covered but not detected, with S/N ~ 6 in the region. Six components were used in the profile fits. We determined the metallicity for this system based on Fe to be [Fe/H] = −1.06 ± 0.06 and based on Zn, [Zn/H] < −0.15. Velocity plots of several lines are shown in Fig. 6.

4.6 Q2051+1950 (z_em = 2.367)

(System A: z_abs = 1.1157). Although Rao et al. (2006) determined log N_HI = 19.26 for this object, we refit the UV STIS spectrum for this object to determine log N_HI = 20.00 ± 0.15. Even with this substantially higher N_HI value, this object appears to have super-solar metallicity. We detected lines of Mg I λ2852, Mg II λλ2796, 2803, Al III λλ1834, Si II λ1808, Cr II λ2056, Mn λλ2576, 2594, 2606, Fe II λλ2260, 2344, 2374, 2382, 2586, 2600 and Zn II λλ2026, 2062. Nine components were used in the profile fits. The Al II λ1670 line is heavily saturated, so only a lower limit could be placed on the column density. The Al III/Al II ratio for this system is Al III/Al II < −0.17. The Ca II λ3934 line is clearly detected, with W_0(3934) = 133 ± 34 mÅ. This system shows strong Fe II absorption features, with [Fe/H] = −0.45 ± 0.15, much higher than typical DLA systems. We also detect Zn II λλ2026, 2062 at >5σ, with [Zn/H] = +0.27 ± 0.18. This system has moderate dust depletion with [Zn/Fe] = +0.72 ± 0.10. Manganese is also slightly overabundant relative to Fe in this system, with [Mn/Fe] = +0.16 ± 0.03. Velocity plots of several lines are shown in Fig. 7.

4.7 Q2352−0028 (z_em = 1.628)

(System A: z_abs = 0.8739). This is a weak sub-DLA system with log N_HI = 19.18 (Rao et al. 2006). Ten components were used in the profile fits. We detect lines of Mg I λ2852, Mg II λλ2796, 2803 and Fe II λλ2344, 2374, 2382, 2586, 2600. The Ti II λ3383 line was covered, but was not detected. This is not unsurprising as this line is weak in most systems. The Al III λ1834, 1862 lines were below the covered wavelengths and could not be measured. The Zn II λλ2026, 2062 lines were not detected at S/N ~ 20 in the region. This system has a low metallicity, with [Fe/H] = −1.17 ± 0.9, and [Zn/H] < −0.14. Velocity plots of several lines are shown in Fig. 8.

(System B: z_abs = 1.0318). This is a sub-DLA system with log N_HI = 19.81 (Rao et al. 2006). Eleven components were used in the profile fitting analysis. Lines of Mg I λ2852, Mg II λλ2796, 2803, Al III λλ1834, 1862, Si II λ1808 and Fe II λλ2260, 2344, 2374, 2382, 2586, 2600 were detected. The Al III λ1854 was partially blended with an interloping feature, but the weaker Al III λ1862 was
Abundances of sub-DLAs at $z \lesssim 1.5$

Figure 5. Same as Fig. 1 but for Q0427−1302.

Figure 6. Same as Fig. 1 but for Q1631+1156.
Figure 7. Same as Fig. 1 but for Q2051+1950.

Figure 8. Same as Fig. 1 but for Q2352−0028A.
Abundances of sub-DLAs at $z \lesssim 1.5$

**Figure 9.** Same as Fig. 1 but for Q2352−0028B.

(System C: $z_{\text{abs}} = 1.2467$). This system is a sub-DLA with log $N_{\text{H}} = 19.60$ (Rao et al. 2006). The complex absorption profile required 15 components to properly fit the system. We detected lines of Mg $\lambda 2852$, Mg $\lambda\lambda 2796, 2803$, Al $\lambda 1670$, Al $\lambda\lambda 1854, 1862$ and Fe $\lambda\lambda 2344, 2374, 2382, 2586, 2600$. This sub-DLA appears to have significant amounts of ionization with Al $\lambda 2852$ $N_{\text{HI}}$ at $S/N \sim 30$ in the region, giving an upper limit on the Zn abundance as $[Zn/H] < -0.51$. This system shows signs of moderate $\alpha$ enhancement with $[Si/Fe] = +0.51 \pm 0.03$. Velocity plots of several lines are shown in Fig. 9.

5 [MN/FE] – NUCLEOSYNTHETIC EFFECTS

Mn and Fe are an interesting pair of elements to study in QSO absorbers for reasons discussed below, and have been investigated in the past by several groups (Pettini et al. 2000; Dessauges-Zavadsky, Prochaska & D’Odorico 2002; Ledoux, Bergeron & Petitjean 2002). The lines of Mn $\lambda\lambda 2576, 2594, 2606$ are usually simultaneously accessible with Fe $\lambda$ lines with the MIKE spectrograph due to the large wavelength coverage available. In Milky Way stars, the Mn abundance seems to have a strong metallicity dependence. A clear trend between [Mn/Fe] and [Fe/H] in the sense that [Mn/Fe] increases near solar values as [Fe/H] increases is also seen (Nissen et al. 2000; McWilliam, Rich & Smecker-Hane 2003; Gratton et al. 2004). This seems to indicate that the nucleosynthetic origin of Mn is in Type Ia SNe, as with the $\alpha$-capture elements which are produced in Type II SNe, $[\alpha/Fe]$ tends to decrease with increasing [Fe/H]. Samland (1998) argue that ~75 per cent of Mn is produced in Type Ia SNe explosions. On the other hand, Timmes, Woosley & Weaver (1995) suggest that metallicity-dependent yields in Type II SNe can also reproduce the observed trends. Feltzing, Fohlman & Bensby (2007) favour metallicity-dependent yields with Type II SNe as the major contributors based on their observations of stellar abundances in the Milky Way and a compilation of other stellar abundances, but note that the Type Ia enrichment scenario is impossible to rule out.

Whatever the underlying production mechanism of Mn may be, there does seem to be a trend between [Mn/Fe] and metallicity. As the condensation temperatures of Mn and Fe are similar, and accordingly have similar levels of depletion especially in the warm and halo ISM of the Milky Way, the relative abundances of these two elements are expected to be mainly nucleosynthetic in origin.

In Fig. 11, we show [Mn/Fe] versus [Zn/H] for these absorbers, as well as ones taken from the literature. Overlayed on the same graph are the data points from Reddy, Lambert & Prieto (2006) from Milky Way stars, and the interstellar abundances from Welty et al. (2001). A clear trend of increasing [Mn/Fe] with increasing [Zn/H] is seen,
Figure 10. Same as Fig. 1 but for Q2352−0028C.

Figure 11. [Mn/Fe] versus [Zn/H] for sub-DLAs, as well as the DLAs with Mn and Fe detections from the literature. The star shaped orange points are Milky Way stellar abundances from Reddy et al. (2006). The sub-DLA points are from these measurements as well as Meiring et al. (2007), Meiring et al. (2008). Also shown are the ISM abundances for the SMC from Welty et al. (2001).
Table 3. Total column densities from the absorbers in this sample.

| QSO         | z_{abs} | log N(H) | Mg I   | Mg II  | Al I   | Al II  | Si II  | Ca II  | Ti II  | Cr II  | Mn II  | Fe II  | Zn II  |
|-------------|---------|----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Q0005+0524  | 0.8514  | 19.08 ± 0.04 | 12.18 ± 0.02 | > 14.32 | – | 13.11 ± 0.04 | – | – | < 11.03 | < 11.88 | < 11.01 | 13.79 ± 0.01 | < 11.24 |
| AOD         | 12.24 ± 0.04 | > 14.13 | 13.13 ± 0.06 | | | | | | | | | | |
| Q012−0122   | 1.3862  | 20.26 ± 0.02 | 11.73 ± 0.03 | > 14.09 | > 13.08 | 12.89 ± 0.02 | 14.43 ± 0.08 | – | < 11.96 | < 11.89 | < 11.41 | 14.24 ± 0.01 | < 11.55 |
| AOD         | 11.75 ± 0.05 | > 13.81 | > 13.07 | 12.83 ± 0.04 | 14.45 ± 0.04 | | | | | | | | |
| Q021+0104A  | 1.3259  | 20.04 ± 0.11 | 12.16 ± 0.04 | > 14.86 | > 13.71 | – | > 14.90 | – | – | < 12.21 | < 11.87 | 14.69 ± 0.01 | < 11.48 |
| AOD         | 12.26 ± 0.06 | > 14.50 | > 13.68 | > 14.86 | | | | | | | | | |
| Q021+0104B  | 1.5756  | 20.48 ± 0.15 | 12.61 ± 0.03 | > 14.57 | – | 12.26 ± 0.08 | 14.88 ± 0.03 | – | – | < 12.58 | < 11.90 | 14.61 ± 0.02 | < 11.95 |
| AOD         | 12.60 ± 0.06 | > 14.51 | 12.31 ± 0.17 | 14.86 ± 0.02 | | | | | | | | | |
| Q0427−1302  | 1.4080  | 19.04 ± 0.04 | – | > 13.74 | 12.20 ± 0.03 | < 11.06 | 13.59 ± 0.03 | – | – | < 11.87 | < 11.65 | 13.36 ± 0.01 | < 11.09 |
| AOD         | > 13.25 | 12.21 ± 0.03 | 13.56 ± 0.04 | | | | | | | | | | |
| Q1631+1156  | 0.9004  | 19.70 ± 0.04 | 12.35 ± 0.06 | > 14.18 | – | – | – | – | 12.13 ± 0.07 | < 11.66 | < 12.65 | < 12.54 | 14.11 ± 0.02 | < 12.18 |
| AOD         | 12.44 ± 0.05 | > 14.04 | – | – | – | – | – | – | 12.22 ± 0.10 | | | | |
| Q2051+1950  | 1.1157  | 20.00 ± 0.15 | 12.64 ± 0.02 | > 14.61 | > 13.70 | 13.53 ± 0.03 | 15.15 ± 0.07 | 12.55 ± 0.04 | – | 12.89 ± 0.10 | 13.21 ± 0.02 | 15.02 ± 0.02 | 12.90 ± 0.10 |
| AOD         | 12.67 ± 0.02 | > 14.44 | > 13.77 | 13.52 ± 0.02 | 15.31 ± 0.12 | 12.59 ± 0.04 | | | | | | | |
| Q2352−0028A | 0.8730  | 19.18 ± 0.09 | 11.85 ± 0.06 | > 14.27 | – | – | – | < 11.01 | < 11.36 | < 12.37 | < 11.46 | 13.48 ± 0.02 | < 11.67 |
| AOD         | 11.84 ± 0.14 | > 14.05 | – | – | – | – | – | < 11.01 | < 11.36 | < 12.37 | < 11.46 | | |
| Q2352−0028B | 1.0318  | 19.81 ± 0.13 | 12.53 ± 0.02 | > 14.94 | – | 13.41 ± 0.02 | 15.49 ± 0.03 | – | – | 12.96 ± 0.06 | < 11.87 | 14.91 ± 0.01 | < 11.93 |
| AOD         | 12.60 ± 0.03 | > 14.58 | 13.41 ± 0.05 | 15.49 ± 0.06 | | | | | | | | | |
| Q2352−0028C | 1.2467  | 19.60 ± 0.24 | 12.33 ± 0.02 | > 15.24 | 13.49 ± 0.02 | 13.39 ± 0.02 | – | – | < 12.17 | < 11.60 | 14.21 ± 0.01 | < 11.53 |
| AOD         | 12.32 ± 0.07 | > 14.39 | 13.42 ± 0.02 | 13.43 ± 0.03 | | | | | | | | | |

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as is seen in the Milky Way. A Spearman rank correlation coefficient for these data was determined to be \( r_S = 0.497 \) with a probability of obtaining this value by chance of 0.003. Kendall’s\( \tau \) was also determined to be \( \tau = 0.359 \), with a probability of no correlation also of 0.003. The absorber sample has a larger dispersion than the stellar abundances from Reddy et al. (2006), which is possibly a result of the combined effects of some differential depletion between Mn and Fe, and the fact that the galaxies sampled via absorption lines are likely from a mixture of morphological types. The two sub-DLA points in Fig. 11 that lie below the stellar points at \([\text{Zn/H}], [\text{Mn/Fe}] \sim (−0.5,−0.4)\) and \((−0.1, −0.3)\) also have the largest associated errors in \([\text{Mn/Fe}], \) but are well within \(\sim 2\sigma\) of the stellar abundances. The apparent optical depth and profile fitting column density determinations of Zn\(Ⅱ\) in these systems agree within the error bars.

We note that the relative abundance ratio of \([\text{Mn/Fe}]\) does not appear to be significantly altered by ionization effects for reasonable estimates of the ionization parameter (Dessauges-Zavadsky et al. 2002; Meiring et al. 2008). A similar trend was seen in Dessauges-Zavadsky et al. (2002) for \([\text{Mn/Fe}]\) as well, albeit with a smaller sample size.

### 6 DISCUSSION

Total ionic column densities are given in Table 3. The abundances for the observed systems are given in Table 4, where we have used the total column densities (i.e. the sum of the column densities in the individual components of a system that were determined via profile fitting method) along with the total \(N_{\text{HI}}\), as given in Table 1, to determine the abundances of these systems. We have not assumed any ionization corrections on these abundances, and have assumed the first ions to be the dominant ionization species of the elements for which these abundances have been determined, namely Zn, Fe, Mn, Cr and Si. Solar systems abundances from Lodders (2003) are also given in Table 4.

Relative abundances of various elements are also given in Table 4, with the column densities also determined from the profile fitting analysis. Along with the metallicities, we give the ratio \([\text{Zn/Fe}]\), which is often used as an indicator of dust depletion. We also provide the ratios of \([\text{Si/Fe}], [\text{Ca/Fe}], [\text{Cr/Fe}]\) and \([\text{Mn/Fe}]\). Finally, we provide ratios of the column densities of the adjacent ions \([\text{Al/Al}]\) and \([\text{Mg/Al}]\) as well as \([\text{Mg/Al}], \) and Fe, and the fact that the galaxies sampled via absorption lines have undergone much different star formation histories than the Magellanic Clouds (LMC) could also shed light on the morphological types of the absorber host galaxies, as the Magellanic clouds have undergone much different star formation histories than the Milky Way (Pagel & Tautvaisiene 1998; Carrera et al. 2008).

The trend of a rising ratio in \([\text{Mn/Fe}]\) with increasing metallicity for QSO absorbers, both DLAs and sub-DLAs, mimics the trend seen in Milky Way stars. A similar comparison with stellar abundances from the Small Magellanic Cloud (SMC) and Large Magellanic Cloud (LMC) could also shed light on the morphological types of the absorber host galaxies, as the Magellanic clouds have undergone much different star formation histories than the Milky Way (Pagel & Tautvaisiene 1998; Carrera et al. 2008).

Similarly, the \([\text{Mn/Fe}]\) ratio would be interesting to study in detail for a large number of systems over a large redshift range as was done for small samples in Dessauges-Zavadsky et al. (2002) and Ledoux et al. (2002). Due to the intrinsic scatter in the data, a large statistical sample is needed to investigate \([\text{Mn/Fe}]\) versus \(z\). The Mn\(Ⅲ\) triplet at \(\sim 2600\ \AA\) is, however, difficult to detect at \(z > 1.75\) as these lines

### Table 4. Abundances and adjacent ion ratios for the absorbers in this sample.

| QSO         | \(N_{\text{HI}}\)     | \([\text{Al/Al}]\) | \([\text{Ca/Al}]\) | \([\text{Cr/Fe}]\) | \([\text{Mn/Fe}]\) |
|-------------|------------------------|--------------------|----------------------|---------------------|---------------------|
| Q0021-0104B | 1.96 ± 0.21            | 1.28 ± 0.04        | 1.12 ± 0.03          | 1.05 ± 0.03         | 1.10 ± 0.03         |
| Q0021-0104A | 1.86 ± 0.22            | 1.29 ± 0.03        | 1.11 ± 0.02          | 1.04 ± 0.02         | 1.09 ± 0.02         |
| Q0021-0104A | 1.86 ± 0.22            | 1.29 ± 0.03        | 1.11 ± 0.02          | 1.04 ± 0.02         | 1.09 ± 0.02         |
| Q0021-0104A | 1.86 ± 0.22            | 1.29 ± 0.03        | 1.11 ± 0.02          | 1.04 ± 0.02         | 1.09 ± 0.02         |
| Q0021-0104A | 1.86 ± 0.22            | 1.29 ± 0.03        | 1.11 ± 0.02          | 1.04 ± 0.02         | 1.09 ± 0.02         |
| Q0021-0104A | 1.86 ± 0.22            | 1.29 ± 0.03        | 1.11 ± 0.02          | 1.04 ± 0.02         | 1.09 ± 0.02         |
| Q0021-0104A | 1.86 ± 0.22            | 1.29 ± 0.03        | 1.11 ± 0.02          | 1.04 ± 0.02         | 1.09 ± 0.02         |
| Q0021-0104A | 1.86 ± 0.22            | 1.29 ± 0.03        | 1.11 ± 0.02          | 1.04 ± 0.02         | 1.09 ± 0.02         |
| Q0021-0104A | 1.86 ± 0.22            | 1.29 ± 0.03        | 1.11 ± 0.02          | 1.04 ± 0.02         | 1.09 ± 0.02         |
| Q0021-0104A | 1.86 ± 0.22            | 1.29 ± 0.03        | 1.11 ± 0.02          | 1.04 ± 0.02         | 1.09 ± 0.02         |
| Q0021-0104A | 1.86 ± 0.22            | 1.29 ± 0.03        | 1.11 ± 0.02          | 1.04 ± 0.02         | 1.09 ± 0.02         |
| Q0021-0104A | 1.86 ± 0.22            | 1.29 ± 0.03        | 1.11 ± 0.02          | 1.04 ± 0.02         | 1.09 ± 0.02         |
| Q0021-0104A | 1.86 ± 0.22            | 1.29 ± 0.03        | 1.11 ± 0.02          | 1.04 ± 0.02         | 1.09 ± 0.02         |
| Q0021-0104A | 1.86 ± 0.22            | 1.29 ± 0.03        | 1.11 ± 0.02          | 1.04 ± 0.02         | 1.09 ± 0.02         |
| Q0021-0104A | 1.86 ± 0.22            | 1.29 ± 0.03        | 1.11 ± 0.02          | 1.04 ± 0.02         | 1.09 ± 0.02         |
| Q0021-0104A | 1.86 ± 0.22            | 1.29 ± 0.03        | 1.11 ± 0.02          | 1.04 ± 0.02         | 1.09 ± 0.02         |
| Q0021-0104A | 1.86 ± 0.22            | 1.29 ± 0.03        | 1.11 ± 0.02          | 1.04 ± 0.02         | 1.09 ± 0.02         |
| Q0021-0104A | 1.86 ± 0.22            | 1.29 ± 0.03        | 1.11 ± 0.02          | 1.04 ± 0.02         | 1.09 ± 0.02         |
| Q0021-0104A | 1.86 ± 0.22            | 1.29 ± 0.03        | 1.11 ± 0.02          | 1.04 ± 0.02         | 1.09 ± 0.02         |
are sometimes blended with telluric features at these redshifts. On the other hand, these lines can be probed with ground-based spectra at $z \gtrsim 0.25$.

It would be interesting to see for the [Mn/Fe] ratio plateaus to a constant value of $\text{[Mn/Fe]} \sim -0.4$ dex as seen in metal-poor stars with $\text{[Fe/H]} \lesssim -1.5$ (McWilliam et al. 2003; Bai et al. 2004). Also, $\text{[Mn/O]}$ would be an interesting abundance ratio to study as O is almost solely produced in Type II SNe, and Fe is produced in both Types Ia and II explosions. $\text{[Mn/O]}$ versus $\text{[O/H]}$ for dwarf spheroidals and the Milky Way show quite distinct trends (see e.g. Feltzing et al. 2007) and as such may shed light on the morphology of these absorption systems. With these elements, however, the task of separating the differential dust depletion between Mn and O and true nucleosynthetic differences may be difficult.

Here, we have presented rest-frame EWs, column densities and abundances for these 10 absorbers based on spectra taken with the MIKE spectrograph. Zn, the preferred metallicity indicator, is detected in only one system (the $z_{\text{abs}} = 1.1157$ system in Q2051+1950), so an estimate of the mean metallicity based on Zn from survival analysis is impossible as survival analysis requires a higher fraction of detections for an accurate estimate of the mean.

Based on the more heavily depleted element Fe which is detected in all systems, the $N_{\text{HI}}$-weighted mean metallicity is $\langle [\text{Fe/H}] \rangle = -0.77 \pm 0.11$. This is nearly 0.7 dex higher than what is seen in DLAs at these redshifts, $\langle [\text{Fe/H}]_{\text{DLA}} \rangle \sim -1.5$, and even higher than the $N_{\text{HI}}$-weighted mean metallicity based on Zn measurements for DLAs at these redshifts (see e.g. Kulkarni et al. 2007 and references therein). In a forthcoming paper, we combine these values with those from our previous work in Meiring et al. (2007, 2008), Khare et al. (2007) and Péroux et al. (2006b) to examine the full sample of high-resolution sub-DLAs at $z < 1.5$ from our MIKE and UVES observations including kinematics, mean metallicities and relative abundances.

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APPENDIX A

A1 $N_{\text{HI}}$ determinations

The systems studied in this work all have known $N_{\text{HI}}$ from HST spectra. For completeness, we provide plots of the Voigt profiles of the Lyman $\alpha$ transition using the best-fitting values of the column density from Rao et al. (2006) (Figs A1 and A2). Due to the low resolution and S/N of these UV spectra, only one component was used in the fits. We show in the following figures the Voigt profiles corresponding to the column densities given by Rao et al. (2006) and convolved with a Gaussian instrumental spread function based on a 2 pixel resolution element, superimposed on the archival data from HST cycle 6 program 6577, cycle 9 program 8569 and cycle 11.
program 9382. We note that the normalization, i.e. the continuum fit that we define may differ from that adopted by Rao et al. (2006). For Q2051+1950, we have revised the fit of Rao et al. (2006) to log $N_{\text{HI}} = 20.00 \pm 0.15$. For all other cases, we find their values completely in agreement. For our continuum fits, a polynomial typically of order 5 or less or a cubic spline was used, and the absorption line itself was excluded from the fitting region. Also overplotted are profiles with H\textsc{I} column densities smaller and larger by 0.15
Abundances of sub-DLAs at $z \lesssim 1.5$

Figure A2. Same as Fig. A1.

dex than the best-fitting values. A bar located below the continuum level in the absorption feature denotes the range of absorption seen in the Mg II profiles in velocity space. For Q0005+0524, a shift of $\sim 200 \, \text{km s}^{-1}$ was applied to align the profile due to apparent inaccuracies in the wavelength calibration of the FOS spectrum. See also Miller, Knezek & Bregman (1999) for more on the FOS pipeline wavelength calibration inaccuracies.

Higher resolution UV spectra covering higher Lyman series transitions (Lyman $\beta$, Lyman $\gamma$, etc.) would help to resolve the effects of the wide spread of the Mg II components and discern abundance differences between components which is not possible with the current lower resolution UV spectra.

A2 Individual fit parameters

Here (in Tables A1–A10) we give the parameters for the fits for each individual system. Radial velocities and effective Doppler parameters of the components are in units of km s$^{-1}$, while the column densities are in cm$^{-2}$. The errors for each component are $1\sigma$ formal errors from FIT6P.

Table A1. Column densities for Q0005+0524, $z_{\text{abs}} = 0.8514$, $N_{\text{H}_1} = 19.08$.

| $v$  | $b_{\text{eff}}$ | Mg I   | Mg II  | Al III | Fe II  |
|------|------------------|--------|--------|--------|--------|
| −26  | 8.6              | (4.24 ± 0.27)E11 | >3.09E13 | (2.71 ± 0.53)E12 | (1.63 ± 0.04)E13 |
| −11  | 6.2              | (5.55 ± 0.32)E11 | >4.18E13 | (4.30 ± 0.68)E12 | (2.87 ± 0.07)E13 |
| 7    | 5.6              | (4.26 ± 0.26)E11 | >7.69E13 | (1.67 ± 0.43)E12 | (1.02 ± 0.03)E13 |
| 35   | 10.3             | (9.78 ± 2.09)E10 | >8.09E12 <3.01 ± 0.21> | E12 | − |
| 145  | 4.7              | −       | −      | >8.09E12 | (6.10 ± 3.43)E11 | (2.36 ± 0.21)E12 |
| 182  | 6.9              | −       | >4.72E13 | (3.44 ± 0.55)E12 | (4.01 ± 0.24)E12 |
| 301  | 9.0              | −       | (9.11 ± 1.39)E11 | − | − |
| 412  | 5.5              | −       | (1.34 ± 1.55)E12 | − | − |
Table A3. Column densities for Q0021+0104, $z_{abs} = 1.3259$, $N_{H1} = 20.04$.

| $v$  | $b_{eff}$ | Mg I   | Mg II  | Al II  | Al III | Si II  | Fe II  |
|------|-----------|--------|--------|--------|--------|--------|--------|
| 231  | 4.1       | –      | (2.00 ± 0.21)E12 | –      | –      | –      | (2.53 ± 0.90)E12 |
| 166  | 9.0       | –      | >1.06E13 | >1.28E12 | >1.07E13 | 9.54 ± 1.23E12 |
| 127  | 13.0      | –      | >6.91E12 | >2.64E12 | 3.78 ± 1.16E12 |
| 104  | 8.4       | –      | >1.27E14 | >5.96E12 | >8.16E13 | 3.42 ± 0.25E13 |
| 9.5  | –         | >2.31E13 | >4.73E12 | >3.54E13 | 1.95 ± 0.18E13 |
| 35   | 13.8      | (7.79 ± 0.88)E11 | >9.89E13 | >1.81E13 | 2.64E14 | 1.06 ± 0.06E14 |
| 8    | 9.0       | (6.60 ± 0.83)E11 | >1.32E14 | >3.56E12 | >2.19E13 | 7.57 ± 0.54E13 |
| 25   | 5.7       | –      | >1.04E13 | >3.42E12 | >6.79E13 | 4.02 ± 0.51E13 |
| 39   | 6.8       | –      | >1.73E14 | >4.44E12 | >9.53E13 | 9.17 ± 0.66E13 |
| 55   | 10.1      | –      | >2.99E12 | >6.42E13 | 5.51 ± 0.43E13 |
| 118  | 14.1      | –      | >1.82E13 | >2.57E12 | 4.97E13 | 2.21 ± 0.19E13 |
| 145  | 9.4       | –      | >6.21E12 | –      | >6.84E12 | 1.29 ± 0.14E13 |

Table A4. Column densities for Q0021+0104, $z_{abs} = 1.5756$, $N_{H1} = 20.48$.

| $v$  | $b_{eff}$ | Mg I   | Mg II  | Al II  | Al III | Si II  | Fe II  |
|------|-----------|--------|--------|--------|--------|--------|--------|
| 339  | 13.6      | –      | (5.37 ± 0.27)E12 | –      | (1.05 ± 0.22)E13 | 2.16 ± 0.42E12 |
| 305  | 8.6       | (8.89 ± 3.67)E10 | (5.44 ± 0.32)E12 | –      | (1.22 ± 0.21)E13 | 2.79 ± 0.39E12 |
| 264  | 6.6       | –      | (6.87 ± 1.27)E11 | –      | –      | –      |
| 197  | 5.5       | –      | (4.00 ± 0.30)E12 | –      | (5.84 ± 0.64)E12 | 2.52 ± 0.37E12 |
| 145  | 12.1      | –      | (3.89 ± 0.28)E12 | –      | (4.01 ± 0.43)E13 | 2.69 ± 0.48E12 |
| 133  | 4.3       | (8.99 ± 3.54)E10 | (4.51 ± 0.77)E12 | –      | (3.09 ± 2.53)E12 | 4.51 ± 0.59E12 |
| 113  | 9.2       | (4.16 ± 0.47)E11 | >6.39E13 | –      | (1.24 ± 0.20)E14 | 2.40 ± 0.14E13 |
| 87   | 10.7      | (2.79 ± 0.45)E11 | >3.11E13 | –      | (5.65 ± 0.66)E13 | 1.53 ± 0.10E13 |
| 63   | 10.1      | (2.98 ± 0.92)E11 | >6.78E13 | (1.82 ± 0.32)E12 | 8.27 ± 2.27E13 | 6.77 ± 1.05E13 |
| 56   | 11.4      | (2.17 ± 1.02)E11 | >1.47E13 | –      | (3.05 ± 2.48)E13 | 3.49 ± 1.65E13 |
| 37   | 13.3      | (2.04 ± 0.54)E11 | >2.32E13 | –      | (8.57 ± 0.98)E13 | 1.17 ± 0.08E14 |
| 65   | 9.7       | (2.95 ± 0.44)E11 | (6.90 ± 0.39)E12 | –      | (1.79 ± 0.25)E13 | 1.19 ± 0.07E13 |
| 37   | 9.1       | (3.48 ± 0.47)E11 | >2.29E13 | –      | (4.39 ± 0.55)E13 | 7.04 ± 0.69E12 |
| 54   | 10.6      | (1.65 ± 0.45)E11 | >3.79E13 | –      | (5.56 ± 0.70)E13 | 2.72 ± 0.17E13 |
| 81   | 11.3      | (6.96 ± 0.59)E11 | >3.16E13 | –      | (8.74 ± 1.06)E13 | 3.96 ± 0.23E13 |
| 106  | 11.8      | (5.93 ± 0.96)E11 | >1.20E13 | –      | (3.57 ± 1.02)E13 | 5.25 ± 2.29E12 |
| 115  | 12.6      | (3.05 ± 0.89)E11 | >2.85E13 | –      | (5.33 ± 0.87)E13 | 3.89 ± 0.27E13 |
| 152  | 9.2       | –      | (5.46 ± 0.31)E12 | –      | (1.18 ± 0.21)E13 | 2.40 ± 0.38E12 |
| 179  | 6.4       | –      | (7.33 ± 1.29)E11 | –      | –      | –      |
| 272  | 4.4       | –      | (9.17 ± 1.35)E11 | –      | –      | –      |

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Table A6. Column densities for Q1631+1156, $z_{	ext{abs}} = 0.9004$, $N_{H} = 19.70$.

| $v$ | $b_{\text{eff}}$ | Mg $\dagger$ | Mg $\ddagger$ | Ca $\ddagger$ | Fe $\ddagger$ |
|-----|------------------|---------------|---------------|---------------|---------------|
| $-67$ | $11.1$ | – | $>1.65\times10^{13}$ | – | $(1.18 \pm 0.06)\times10^{13}$ |
| $-35$ | $8.0$ | $(3.93 \pm 1.39)\times10^{11}$ | $>2.69\times10^{13}$ | $(4.67 \pm 1.19)\times10^{11}$ | $(3.20 \pm 0.20)\times10^{13}$ |
| $-20$ | $8.5$ | $(1.80 \pm 0.30)\times10^{12}$ | $>2.48\times10^{13}$ | $(4.27 \pm 1.19)\times10^{11}$ | $(6.24 \pm 0.43)\times10^{13}$ |
| $6$ | $7.6$ | – | $>7.98\times10^{13}$ | $(4.70 \pm 1.16)\times10^{11}$ | $(2.13 \pm 0.13)\times10^{13}$ |
| $56$ | $8.0$ | – | $(3.29 \pm 0.29)\times10^{12}$ | – | $(1.89 \pm 0.33)\times10^{12}$ |
| $88$ | $10.9$ | – | $(2.29 \pm 0.24)\times10^{12}$ | – | – |

Table A7. Column densities for Q2051+1950, $z_{\text{abs}} = 1.1157$, $N_{H} = 20.00$.

| $v$ | $b_{\text{eff}}$ | Mg $\dagger$ | Mg $\ddagger$ | Al $\ddagger$ | Al $\ddagger$ | Si $\ddagger$ |
|-----|------------------|---------------|---------------|--------------|--------------|--------------|
| $-19$ | $8.1$ | $(2.95 \pm 0.17)\times10^{12}$ | – | – | – | – |
| $1$ | $10.6$ | $(3.25 \pm 0.35)\times10^{11}$ | $>2.82\times10^{13}$ | – | $(2.64 \pm 0.44)\times10^{12}$ | – |
| $25$ | $9.6$ | $(7.17 \pm 0.44)\times10^{11}$ | $>8.11\times10^{13}$ | $(3.12 \pm 0.47)\times10^{12}$ | – | – |
| $51$ | $11.1$ | $(9.24 \pm 0.60)\times10^{11}$ | $>7.42\times10^{13}$ | $(4.18 \pm 0.65)\times10^{12}$ | – | – |
| $68$ | $8.0$ | $(1.79 \pm 0.11)\times10^{12}$ | $>5.94\times10^{13}$ | $(1.03 \pm 0.14)\times10^{13}$ | $(1.01 \pm 0.18)\times10^{15}$ | – |
| $88$ | $8.2$ | $(4.00 \pm 0.37)\times10^{11}$ | $>8.17\times10^{13}$ | $(3.31\times10^{12}$ | $(5.86 \pm 0.74)\times10^{12}$ | – |
| $105$ | $7.4$ | $(2.46 \pm 0.37)\times10^{11}$ | $>2.92\times10^{13}$ | $(3.48 \pm 0.63)\times10^{12}$ | – | – |
| $144$ | $11.9$ | – | $(2.17 \pm 0.13)\times10^{12}$ | – | $(8.78 \pm 3.70)\times10^{11}$ | – |
| $19$ | $9.8$ | – | $(6.08\times10^{13}$ | $(3.34 \pm 0.55)\times10^{12}$ | $(3.94 \pm 1.36)\times10^{14}$ | – |

| $v$ | $b_{\text{eff}}$ | Ca $\ddagger$ | Mn $\ddagger$ | Cr $\ddagger$ | Fe $\ddagger$ | Fe $\ddagger$ |
|-----|------------------|---------------|---------------|--------------|--------------|--------------|
| $-19$ | $8.1$ | – | – | – | $(2.68 \pm 0.71)\times10^{12}$ | – |
| $1$ | $10.6$ | – | $(3.91 \pm 1.61)\times10^{11}$ | – | $(8.77 \pm 0.40)\times10^{13}$ | $(7.90 \pm 0.92)\times10^{11}$ |
| $5$ | $9.6$ | $(7.05 \pm 1.29)\times10^{11}$ | $(2.27 \pm 0.18)\times10^{12}$ | $(2.46 \pm 1.15)\times10^{12}$ | $(1.59 \pm 0.09)\times10^{14}$ | $(1.34 \pm 0.09)\times10^{12}$ |
| $51$ | $11.1$ | $(1.21 \pm 0.17)\times10^{12}$ | $(2.35 \pm 0.21)\times10^{12}$ | – | $(1.54 \pm 0.10)\times10^{14}$ | $(1.12 \pm 0.11)\times10^{12}$ |
| $68$ | $8.0$ | $(8.85 \pm 1.51)\times10^{11}$ | $(4.88 \pm 0.27)\times10^{12}$ | $(5.37 \pm 1.30)\times10^{12}$ | $(2.81 \pm 0.34)\times10^{14}$ | $(2.59 \pm 0.12)\times10^{12}$ |
| $88$ | $8.2$ | $(4.02 \pm 1.14)\times10^{11}$ | $(2.54 \pm 0.19)\times10^{12}$ | – | $(1.85 \pm 0.15)\times10^{14}$ | $(8.77 \pm 0.87)\times10^{11}$ |
| $105$ | $7.4$ | $(3.49 \pm 1.18)\times10^{11}$ | $(1.55 \pm 0.19)\times10^{12}$ | – | $(1.06 \pm 0.09)\times10^{14}$ | $(3.84 \pm 0.90)\times10^{11}$ |
| $144$ | $11.9$ | – | $(5.47 \pm 1.55)\times10^{11}$ | – | $(5.22 \pm 0.77)\times10^{12}$ | – |
| $19$ | $9.8$ | – | $(9.87 \pm 1.77)\times10^{11}$ | – | $(5.83 \pm 0.32)\times10^{13}$ | $(8.01 \pm 1.00)\times10^{11}$ |

Table A8. Column densities for Q2352−0028, $z_{\text{abs}} = 0.8739$, $N_{H} = 19.18$.

| $v$ | $b_{\text{eff}}$ | Mg $\dagger$ | Mg $\ddagger$ | Fe $\ddagger$ |
|-----|------------------|---------------|---------------|--------------|
| $-146$ | $9.8$ | – | $(1.32 \pm 0.15)\times10^{12}$ | $(5.18 \pm 3.11)\times10^{11}$ |
| $-122$ | $11.8$ | – | $(4.03 \pm 0.23)\times10^{12}$ | $(1.80 \pm 0.35)\times10^{12}$ |
| $-94$ | $11.8$ | – | $(1.62 \pm 0.16)\times10^{12}$ | $(1.10 \pm 0.34)\times10^{12}$ |
| $-46$ | $9.2$ | $(1.91 \pm 0.58)\times10^{11}$ | $>1.41\times10^{13}$ | $(2.97 \pm 0.32)\times10^{12}$ |
| $-15$ | $9.0$ | $(2.69 \pm 0.67)\times10^{11}$ | $>2.90\times10^{13}$ | $(8.25 \pm 0.41)\times10^{12}$ |
| $0$ | $7.5$ | $(1.33 \pm 0.60)\times10^{11}$ | $>7.27\times10^{13}$ | $(6.27 \pm 0.38)\times10^{12}$ |
| $26$ | $6.4$ | – | $>6.27\times10^{12}$ | $(2.30 \pm 0.39)\times10^{12}$ |
| $34$ | $7.7$ | – | $>3.92\times10^{13}$ | $(1.62 \pm 0.41)\times10^{12}$ |
| $58$ | $5.6$ | $(1.16 \pm 0.51)\times10^{11}$ | $>1.57\times10^{13}$ | $(4.03 \pm 0.30)\times10^{12}$ |
| $79$ | $7.4$ | – | $>3.64\times10^{12}$ | $(1.30 \pm 0.29)\times10^{12}$ |
Table A9. Column densities for Q2352−0028,  \( z_{\text{abs}} = 1.0318 \), \( N_{\text{HI}} = 19.81 \).

| \( v \)  | \( b_{\text{eff}} \) | \( \text{Mg}\,\text{I} \)        | \( \text{Mg}\,\text{II} \)       | \( \text{Al}\,\text{III} \)     | \( \text{Si}\,\text{II} \)     | \( \text{Cr}\,\text{II} \)     | \( \text{Fe}\,\text{II} \)     |
|-------|-----------------|---------------------------------|---------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| −111  | 6.5             | 1.23 ± 0.15E12                  | −                               | (1.36 ± 0.52)E14              | −                             | (2.26 ± 0.44)E12              |
| −77   | 11.1            | (8.43 ± 0.54)E11 > 2.54E14      | (1.66 ± 0.47)E12                | (2.83 ± 0.65)E14              | −                             | (6.93 ± 0.23)E13              |
| −53   | 9.4             | (5.54 ± 0.78)E11 > 1.15E13      | −                               | −                             | −                             | (7.02 ± 0.55)E13              |
| −46   | 8.0             | > 2.83E13                       | (2.67 ± 0.76)E12                | (3.57 ± 1.05)E14              | −                             | (1.07 ± 0.08)E14              |
| −28   | 7.6             | (3.89 ± 0.42)E11 > 9.56E13      | (3.01 ± 0.49)E12                | (2.49 ± 0.60)E14              | −                             | (4.41 ± 0.20)E13              |
| 0     | 8.8             | (1.35 ± 0.36)E11 > 3.10E13      | −                               | (2.04 ± 0.61)E14              | −                             | (4.99 ± 0.21)E13              |
| 18    | 10.2            | (3.08 ± 0.41)E11 > 1.31E14      | (3.83 ± 0.53)E12                | (4.52 ± 0.70)E14              | (2.12 ± 0.77)E12              | (1.20 ± 0.04)E14              |
| 48    | 6.4             | (1.76 ± 0.36)E11 > 8.44E13      | (2.04 ± 0.44)E12                | −                             | −                             | (4.24 ± 0.21)E13              |
| 66    | 8.9             | (8.84 ± 0.59)E11 > 3.00E13      | (6.25 ± 0.62)E12                | (5.99 ± 0.72)E14              | (4.07 ± 0.77)E12              | (1.45 ± 0.06)E14              |
| 88    | 8.4             | (6.30 ± 0.48)E11 > 1.77E14      | (6.11 ± 0.60)E12                | (4.81 ± 0.67)E14              | (2.88 ± 0.72)E12              | (1.51 ± 0.06)E14              |
| 111   | 4.0             | (9.74 ± 2.96)E10 > 1.92E13      | −                               | −                             | −                             | (4.71 ± 0.47)E12              |

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Table A10. Column densities for Q2352−0028,  \( z_{\text{abs}} = 1.2467 \), \( N_{\text{HI}} = 19.60 \).

| \( v \)  | \( b_{\text{eff}} \) | \( \text{Mg}\,\text{I} \)        | \( \text{Mg}\,\text{II} \)       | \( \text{Al}\,\text{III} \)     | \( \text{Si}\,\text{II} \)     | \( \text{Fe}\,\text{II} \)     |
|-------|-----------------|---------------------------------|---------------------------------|-------------------------------|-------------------------------|-------------------------------|
| −210  | 9.5             | −                               | > 5.33E12                       | −                             | (3.37 ± 0.74)E12              |
| −184  | 10.9            | −                               | > 1.98E12                       | −                             | −                             |
| −152  | 7.9             | (1.49 ± 0.37)E11 > 3.60E13      | −                               | (5.71 ± 0.77)E12              |
| −109  | 12.7            | −                               | > 4.54E12                       | −                             | −                             |
| −87   | 8.9             | −                               | > 6.93E12                       | (1.41 ± 0.25)E12              | (1.79 ± 0.78)E12              |
| −66   | 9.3             | (2.73 ± 0.43)E11 > 2.03E14      | (7.92 ± 0.53)E12                | (4.63 ± 0.23)E13              |
| −31   | 8.9             | −                               | > 1.44E14                       | (4.27 ± 0.34)E12              | (8.28 ± 0.85)E12              |
| 6     | 7.8             | (2.88 ± 0.44)E11 > 2.15E14      | (3.95 ± 0.34)E12                | (1.12 ± 0.10)E13              |
| 21    | 5.7             | (5.34 ± 0.56)E11 > 1.80E14      | (1.69 ± 0.25)E12                | (2.03 ± 0.15)E13              |
| 50    | 4.0             | (2.40 ± 0.41)E11 > 5.91E14      | (5.28 ± 1.75)E11                | (8.61 ± 0.96)E12              |
| 77    | 6.6             | −                               | > 1.64E12                       | −                             | −                             |
| 108   | 11.6            | (1.84 ± 0.41)E11 > 1.60E13      | (1.99 ± 0.27)E12                | (5.54 ± 0.82)E12              |
| 135   | 4.5             | −                               | > 2.78E12                       | −                             | (2.79 ± 0.67)E12              |
| 163   | 10.5            | (4.83 ± 0.48)E11 > 3.40E14      | (2.53 ± 0.28)E12                | (4.93 ± 0.22)E13              |
| 202   | 7.9             | −                               | > 2.19E12                       | −                             | −                             |