AN IMAGING AND SPECTROSCOPIC STUDY OF THE z_{abs} = 3.38639 DAMPED Lyα SYSTEM IN Q0201 + 1120: CLUES TO STAR FORMATION AT HIGH REDSHIFT

SARA L. ELLISON
Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, UK; and European Southern Observatory, St. Alonso de Córdova 3107, Vitacura, Casilla 19001, Santiago 19, Chile

MAX PETTINI
Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, UK

AND

CHARLES C. STEIDEL² AND ALICE E. SHAPLEY
Palomar Observatory, 105-24, California Institute of Technology, 1201 East California Boulevard, Pasadena, CA 91125

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ABSTRACT

We present the results of a series of imaging and spectroscopic observations aimed at identifying and studying the galaxy responsible for the z_{abs} = 3.38639 damped Lyα system in the z_{em} = 3.61 quasar Q0201 + 1120. We find that the damped Lyα systems (DLA) is part of a concentration of matter that includes at least four galaxies (probably many more) over linear comoving dimensions greater than 5 h^{-1} Mpc. The absorber may be a 0.7L^* galaxy at an impact parameter of 15 h^{-1} kpc, but follow-up spectroscopy is still required for positive identification. The gas is turbulent, with many absorption components distributed over ~270 km s^{-1} and a large spin temperature, T_s ~ 4000 K. The metallicity is relatively high for this redshift, Z_{DLA} \approx 1/20 Z_{\odot}. From consideration of the relative ratios of elements that have different nucleosynthetic timescales, it would appear that the last major episode of star formation in this DLA occurred at z \geq 4.3, more than \sim 500 Myr prior to the time when we observe it.

Subject headings: cosmology: observations — galaxies: abundances — galaxies: evolution — quasars: absorption lines — quasars: individual (Q0201 + 1120)

On-line material: color figures

1. INTRODUCTION

The study of quasar (QSO) absorption lines is a unique tool to investigate the high-redshift universe on a variety of scales, ranging from the intergalactic medium to protogalaxies. Since the detection of material intercepting our line of sight to a QSO is dependent only on the column density of gas and the luminosity of the quasar, this is a particularly powerful and sensitive technique for probing the chemical composition and physical conditions in the interstellar media (ISM) of high-z galaxies.

Damped Lyα systems (DLAs) are the highest column density [N(H I) \geq 2 \times 10^{20} atoms cm^{-2}] absorbers identified in QSO spectra and the major contributors to the census of neutral gas available for star formation. DLAs therefore are widely believed to be the absorption signatures of galaxies in early stages of evolution; the study of their associated metal lines has provided us with the first accurate measurements of the abundances of a wide variety of chemical elements at high z (Lu et al. 1996; Prochaska & Wolfe 1999). Indeed, measuring the abundances in the ISM of DLAs not only gives a direct view of the evolving chemistry of galaxies over time but is also a valuable test bed for supernova models and their theoretical yields (e.g., Pettini et al. 2000).

However, the exact nature of DLAs is still a contentious issue. Results from early DLA surveys (e.g., Wolfe et al. 1986; Lanzetta et al. 1991) led to the proposal that these systems trace the progenitors of present-day spirals. More recently, Prochaska & Wolfe (1997, 1998) have argued that this hypothesis is further supported by the kinematics of the metal absorption lines, which they can best explain with large rotating disks with velocities \vr_{rot} \approx 200 \mbox{ km \ s^{-1}} (although see Ledoux et al. 1998). On the other hand, the presence of such massive disks at z \sim 3 is in stark contrast with the predictions of hierarchical cold dark matter models (e.g., Kauffmann 1996) where galaxies at high redshifts are relatively compact and underluminous. In such models, the kinematics of merging protogalactic clumps also can reproduce the shapes of the absorption lines (Haehnelt, Steinmetz, & Rauch 1998; McDonald & Miralda-Escudé 1999; Gardner et al. 1999). From the point of view of their chemical enrichment, it was shown by Pettini et al. (1997) that the distribution of DLA metallicities is displaced to lower values relative to those of the thin and thick disk stellar populations of the Milky Way (see also Wolfe & Prochaska 1998).

At intermediate redshifts the picture is a little clearer. Direct imaging with the Hubble Space Telescope (HST) of galaxies associated with DLAs at z \leq 1 has revealed a range of morphologies with only a minority of spirals (Le Brun et al. 1997; Rao & Turnshek 1998; Lane 2000; Pettini et al. 2000). However, there are still concerns regarding sample bias. An absorption system at z \leq 1.5 can only be recognized as a DLA with HST ultraviolet spectroscopy (or 21 cm absorption, but such systems are rare). Thus, QSOs behind metal- and presumably dust-rich DLAs may well be underrepresented in existing surveys, given the bright magnitude limit for spectroscopy imposed by the relatively small aperture of HST. Since B-band luminosity and metal-
licity are related (e.g., Kobulnicky & Zaritsky 1999), HST-selected DLAs are likely to be biased in favor of absorbers of low luminosity and metallicity.

In order to make further progress on these issues, it is necessary to bring together all the information provided by deep imaging, kinematics, and chemical abundance studies into one coherent picture. In this paper we explore this approach for a high-redshift DLA in the direction of the QSO Q0201 +1120, which we have targeted with a number of different observations.

The compact, flat-spectrum, radio source PKS 0201+13 with a faint (R = 19.5) optical counterpart (Condon, Hicks, & Jauncey 1977) was identified as a z_{abs} = 3.61 QSO by White, Kinney, & Becker (1993), who also reported the presence of a strong DLA at z_{abs} = 3.3875 with an estimated N(H I) = 2.5 × 10^{21} cm^{-2}. This value of the neutral hydrogen column density is sufficiently high to produce absorption in the redshifted 21 cm line against the background radio source (de Bruyn, O'Dea, & Baum 1996; Briggs, Brinks, & Wolfe 1997), although there is still some uncertainty about the reality of these weak detections (Kanekar & Chengalur 1997). Here we present deep imaging, both from the ground and with HST, of the field of Q0201 +1120 aimed at detecting the galaxy responsible for the DLA. In addition, we have obtained intermediate- and low-resolution spectroscopy of the QSO and of a number of faint sources in its proximity revealed by our images. High-resolution spectroscopy of the DLA is used to study its chemical composition and velocity structure. All these data are scrutinized for clues to the nature of the object producing the damped Lyα system.

Unless otherwise stated, we use a Ω_m = 0.3, Ω_λ = 0.7 cosmology; h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}, and all redshifts reported in this paper are vacuum heliocentric.

2. OBSERVATIONS

Table 1 gives relevant details of the observations, which we now briefly discuss. The top panel of Figure 1 shows a new spectrum of Q0201 +1120 covering the wavelength range 3500–8000 Å, obtained with the Kast double spectrograph of the Shane 3.0 m telescope at Lick Observatory. The spectral resolution is ~4.5 Å, a factor of ~2 better than the discovery spectrum by White et al. (1993). We confirm both the redshift of the QSO (within the errors of measurement) and the presence of a strong damped Lyα line near 5330 Å; we defer precise measurements of the absorption redshift and neutral hydrogen column density to §§ 2.3.1 and 3.1, respectively, where we present the analysis of much higher resolution echelle observations.

2.1. Imaging

The field of Q0201 +1120 was imaged with the (COSMIC; Carnegie Observatories Spectroscopic Multislit and Imaging Camera Kells et al. 1998) at the prime focus of the Palomar 5 m Hale telescope in the U, V, R, I photometric system designed by Steidel & Hamilton (1993) to detect primarily galaxies with redshifts in the interval 2.7 ≤ z ≤ 3.4. The thinned, antireflection-coated Tektronix 2048 × 2048 CCD covers a 9.7 × 9.7 field sampled with a scale of 0.7′′ pixel^{-1}. The seeing measured from the stacked images was ~0′′7–0′′9 FWHM, and the 1 σ surface brightness limits are ~28.56, 28.73, and 27.95 (AB) mag arcsec^{-2} in U, R, and I, respectively. However, the non-negligible foreground extinction in this direction [E(B−V) = 0.147; Schlegel, Finkbeiner, & Davis 1998] makes this field less deep than most of the others observed in our Lyman break survey. Figure 2 shows contour plots of the central 30′′ of the I image before (left) and after (right) subtraction of the QSO image (achieved by appropriate scaling of the point-spread function [PSF] determined from nearby stars).

We also acquired an image of this field with the Wide Field Planetary Camera 2 (WFPC2) on HST through the F606W filter. To produce the final image shown in Figure 3, we combined 10 individual CCD frames by “drizzling” onto a master output pixel grid; the subtraction of the QSO used a careful modeling of the PSF appropriate for the color of the QSO and its position on the chip. Further details of the data reduction procedure can be found in Pettini et al. (2000).

A number of faint sources are present near the QSO. The objects of interest are labeled in Figures 2 and 3, and their relevant parameters are collected in Table 2; the photometry includes corrections for foreground reddening. Galaxies G1 and G3 are unlikely to be associated with the damped Lyα system since they are both detected in the 6066 Å line

| Object/Field   | Telescope | Instrument | Filter/Grating | Integration Time (s) |
|----------------|-----------|------------|----------------|----------------------|
| Q0201 +1120    | Hale 5 m  | COSMIC     | U              | 27000                |
| Hale 5 m       | COSMIC     | G          | 7200           |
| Hale 5 m       | COSMIC     | I          | 3600           |
| HST            | F606W     |            |                |
| Lick 3 m       | Keck 10 m | HIRES      |                |
| Keck 10 m      | LRS       | 300/5000   | 10800          |
| Galaxy oM6     | Keck 10 m | LRS       | 300/5000       |
| Galaxy m32     | Keck 10 m | LRS       | 300/5000       |
| Galaxy c10     | Keck 10 m | LRS       | 300/5000       |
| Galaxy oMD26   | Keck 10 m | LRS       | 300/5000       |

TABLE 1

SUMMARY OF OBSERVATIONS

| Object/Field | Telescope | Instrument | Filter/Grating | Integration Time (s) |
|--------------|-----------|------------|----------------|----------------------|
| Q0201 +1120  | Hale 5 m  | COSMIC     | U              | 27000                |
| Hale 5 m     | COSMIC    | G          | 7200           |
| Hale 5 m     | COSMIC    | I          | 3600           |
| HST          | F606W     |            |                |
| Lick 3 m     | Keck 10 m | HIRES      |                |
| Keck 10 m    | LRS       | 300/5000   | 10800          |
| Galaxy oM6   | Keck 10 m | LRS       | 300/5000       |
| Galaxy m32   | Keck 10 m | LRS       | 300/5000       |
| Galaxy c10   | Keck 10 m | LRS       | 300/5000       |
| Galaxy oMD26 | Keck 10 m | LRS       | 300/5000       |
QSO. However, the WFPC2 F606W magnitudes of all the objects of interest here are consistent with the $R$ and $G - R$ ground-based measurements in Table 2. Finally, note that the source oM6, which appears elongated in Figure 2, is clearly resolved by HST into two components, separated by 1′23.

2.2. Low-Resolution Spectroscopy

We obtained spectroscopic observations of Lyman break galaxy (LBG) candidates in the field of Q0201 + 1120 with the Low Resolution Imaging Spectrograph (LRIS; Oke et al. 1995) on the Keck I Telescope, using different slit masks.
each covering approximately 4' × 7'. Exposure times were 2.5–3 hr per mask in separate 1800 s integrations; with the 300 groove mm⁻¹ grating the resolution of the spectra is ~12.5 Å. These observations resulted in 27 spectroscopically confirmed LBGs with secure redshifts. The object oM6 was among those observed; its spectrum, reproduced in the lower panel of Figure 1, exhibits a prominent Lyα emission line at z_em = 3.645. In some of the exposures the two components of oM6 are partially resolved, showing that the Lyα emission line is stronger in the western component of the pair in Figure 3.

The emission line appears to be spectrally resolved; its profile is symmetric with FWHM ≈ 450 km s⁻¹ after correction for the instrumental resolution. We measure a line flux f_Lyα = (8.7 ± 0.3) × 10⁻¹⁷ ergs s⁻¹ cm⁻², which corresponds to a Lyα luminosity L_Lyα ≈ 5.2 × 10⁴² h⁻² ergs s⁻¹ in our cosmology. The difference in redshift between oM6 and Q0201+1120 is only +465 km s⁻¹, well within the uncertainties (both systematic and random) in the determination of the QSO systemic redshift from the broad emission lines. We conclude that the object oM6 is not the DLA absorber, but it is associated with the QSO, from which it is separated by only ~19 h⁻¹ kpc.

There are several other known examples of such QSO companions; the properties of oM6 are similar, for instance, to those of the Lyα emitter at z = 4.695 near the QSO BR 1202−0725 discussed by Hu, McMahon, & Egami (1996). What is particularly interesting, in the case of oM6, is the clear detection of a stellar continuum (see Fig. 1). In at least this case, the companion appears to be a galaxy, possibly in the process of merging with the QSO host (Cen 2000), rather than simply a gas cloud lit up in Lyα by its proximity to the QSO. At z ≈ 3 our R filter samples the rest-frame far-UV spectrum produced by the integrated population of O and B stars and thus provides a measure of the star formation rate (SFR). With the transformation discussed by Pettini et al. (1998), R = 23.97 corresponds to SFR ≈ 12 h⁻³ M_☉ yr⁻¹ in our cosmology. Correcting for dust reddening of the UV continuum as described in Adelberger & Steidel (2000), we find that G − R = 1.34 implies E(B − V) = 0.079 and an extinction at 1500 Å A_1500 = 0.9 mag. Thus, the dust-corrected SFR is ≈ 28 h⁻³ M_☉ yr⁻¹. For comparison, assuming case B recombination and Kennicutt's (1983) calibration, L_Lyα ≈ 5.2 × 10⁴² h⁻² ergs s⁻¹ would imply only SFR ≈ 5 h⁻³ M_☉ yr⁻¹—even if the Lyα emission line were produced entirely by stellar photoionization, which seems unlikely in this instance given the QSO proximity. Evidently, there is significant suppression of Lyα photons within the stellar H II regions of oM6, as is normally the case in star-forming galaxies at high and low

| Name       | ΔR.A. (arcsec)¹ | ΔDecl. (arcsec)¹ | B     | G − B | U_g − G | Redshift (Mpc) | Δr (Mpc)² |
|------------|----------------|-----------------|-------|-------|---------|----------------|-----------|
| Q0201 + 1120…… | 0.0            | 0.0             | 19.23 | 0.93  | ≥ 5.20  | 3.638          | 0.0       |
| G1         | +0.9           | +0.4            | 22.23 | 1.48  | 1.63    | …              | …         |
| G2         | +2.3           | −0.9            | 25.3  | 0.5   | > 1.7   | …              | …         |
| G3         | +3.4           | −2.7            | 26.3  | 0.2   | 0.3     | …              | …         |
| oM6        | +1.3           | −3.5            | 23.97 | 1.34  | > 2.6   | 3.645          | 0.085     |
| m32        | +113.5         | +71.5           | 25.21 | 0.79  | > 1.99 | 3.645          | …         |
| c10        | −116.6         | +166.1          | 24.07 | 0.70  | > 2.68 | 3.366          | 4.61      |
| oMD26      | −98.0          | +204.7          | 24.72 | 0.83  | ≥ 1.72  | 3.368          | 5.15      |

¹ Relative to Q0201 + 1120.
² Comoving distance from the Q0201 + 1120 sight line at z = 3.37 (Ω_M = 0.3, Ω_Λ = 0.7, h = 1).
³ Formally detected in U_g at the 1 σ level.
⁴ The photometry of G2 is uncertain because of its proximity to G1 and the QSO.
Returning to Figure 1, it can also be seen that, although the signal-to-noise ratio (S/N) is not high, there appears to be a strong absorption feature near 5300 Å, which we tentatively identify as a damped Ly\(\alpha\) line at \(z_{\text{abs}} = 3.364\) with \(N(\text{H} \text{I}) = 4 \times 10^{20} \text{ cm}^{-2}\) (see inset). The difference in redshift from the \(z_{\text{abs}} = 3.3875\) DLA in the spectrum of the QSO, corresponding to \(\Delta v \approx -1600 \text{ km s}^{-1}\), is far too high for this to be the same absorbing galaxy covering both sight lines, and we therefore must be dealing with two separate absorbers. Furthermore, two out of the other 26 LBGs with spectroscopic redshifts in this field were found to be at similar redshift as the two DLAs. They are c10 and oMD26 at \(z = 3.366\) and 3.368, respectively; their spectra are shown in Figure 4, and relevant properties are listed in Table 2. Thus, we have found four objects at \(z \approx 3.37\) in this field, two detected in their stellar continua as Lyman break galaxies, and the other two identified via absorption lines in the spectra of higher redshift sources.

Unfortunately, our LRIS spectroscopy did not include object G2; in any case it would be very difficult to separate it from the QSO, which is only 2.9 away and 6 mag brighter. If this is the DLA, then its impact parameter from the QSO sight line is 15 \(h^{-1}\) kpc (proper distance). Our estimated \(R \approx 25.3\) would imply that this galaxy has a rest-frame UV luminosity of about \(0.7L^*\), adopting \(R = 24.54 = L^* \) at \(z \approx 3\) from the LBG luminosity function derived by Adelberger & Steidel (2000) for our cosmology, and making the appropriate luminosity distance and \(k\)-corrections. If this galaxy turns out not to be at the redshift of the DLA, then the absorber must be fainter than \(R \approx 26.0\), or \(\approx 0.4L^*\) (with the usual caveats that we would miss brighter objects if located directly underneath the QSO image or if they are extended and of low surface brightness).

The remaining 24 LBGs are at redshifts between 2.167 and 3.802 and include a galaxy, m32, at \(z = 3.645\), the same redshift (within the errors) as Q0201 + 1120 and oM6. Its spectrum is also shown in Figure 4; its projected separation of 134" from the QSO sight line (Table 2) corresponds to a comoving distance of 3.14 \(h^{-1}\) Mpc.

Summarizing the results of this section, our deep Palomar and \(HST\) imaging data have shown that the strong DLA at \(z_{\text{abs}} = 3.3875\) in front of Q0201 + 1120 is part of a concentration of galaxies that includes at least four objects distributed over linear comoving dimensions of more than 5 \(h^{-1}\) Mpc. The absorber is either a \(\approx 0.7L^*\) galaxy at an impact parameter of 15 \(h^{-1}\) kpc or is likely to be fainter than about 0.4\(L^*\). We have also identified two galaxies that are at the same redshift as the QSO; one of them is at a projected separation of only 19 \(h^{-1}\) kpc from the QSO.

### 2.3. High-Resolution Spectroscopy

In order to study in more detail the physical properties of the gas giving rise to the DLA system in Q0201 + 1120, we used the High Resolution Echelle Spectrograph (HIRES) on the Keck I Telescope (Vogt 1992) to record the spectrum of the QSO between 4500 and 6900 Å. With the 0.86 entrance slit, the spectral resolution was 6 km s\(^{-1}\) FWHM. The observations extended over two nights; the total integration time was 40,500 s, typically made up of 4500 s long individual exposures.

The data were reduced using T. Barlow’s HIRES reduction package MAKEE.\(^3\) Having bias subtracted and flat-fielded the individual CCD frames, MAKEE performs an optimally weighted extraction followed by wavelength calibration (on a vacuum heliocentric scale) using reference spectra of a ThAr hollow cathode lamp. Before joining the echelle orders, the summed data array was mapped onto a linear wavelength grid (0.03 Å pixel\(^{-1}\)); the resultant one-dimensional spectrum was then normalized to the QSO continuum determined by fitting splines to regions free of absorption lines. The signal-to-noise ratio measured in the continuum is \(S/N = 10 - 20\); with \(R = 19.5\), Q0201 + 1120 is at the limit of the HIRES capability. The spectrum extends from 1026 to 1573 Å in the rest frame of the \(z_{\text{abs}} = 3.3875\) DLA.

#### 2.3.1. The Redshift of the DLA

Figure 5 is a montage of selected metal absorption lines in the DLA. The high resolution of the echelle data reveals a complex absorption system with many individual components spread over a velocity interval of \(\sim 270 \text{ km s}^{-1}\). The two components with the largest optical depths are centered at redshifts \(z_{\text{abs}} = 3.38632\) and 3.38684; in the strongest transitions (O I \(\lambda\)1302 and C II \(\lambda\)1334), they form a black absorption feature centered at \(z_{\text{abs}} = 3.38639\), which we take as the reference redshift for the DLA.

\(^3\) MAKEE is available at http://www2.keck.hawaii.edu:3636/realpublic/inst/hires/makeewww.
source. Three groups have searched for the 21 cm line in this damped system, with conflicting results. De Bruyn et al. (1996), using the Westerbork synthesis radio telescope, found an absorption line at \( z = 3.38699 \) with optical depth \( \tau = 0.085 \pm 0.02 \) and FWHM = 9 ± 2 km s\(^{-1}\). A detection was also reported by Briggs et al. (1997) using the Arecibo telescope, but the feature in their spectrum had significantly different parameters: \( z = 3.38716 \pm 0.00007 \), \( \tau = 0.037 \pm 0.008 \), and FWHM = 23 ± 5 km s\(^{-1}\). Finally, Kanekar & Chengalur (1997) could see no absorption at all in data obtained with the Ooty radio telescope and of comparable sensitivity to those of the other two studies.

Here we note that the two values of \( z_{21} \) above correspond to velocities of +41 and +53 km s\(^{-1}\) relative to the redshift \( z_{abs} = 3.38639 \), which we have adopted as the zero point for the metal absorption lines. Referring to Figure 5, it can be seen that these velocities fall on the red edge of the main group of absorption components, where the optical depth in the metal lines is not high. It seems unlikely that there should be such a large displacement between the optical depth of H I and those of all the other metal absorption lines (including neutral species such as O I and N I), which, as can be seen from Figure 5, agree so precisely in velocity among themselves (note that the damped Ly\( \alpha \) line itself is too broad to constrain the absorption redshift of H I within useful limits). First, the redshift differences between radio and optical data are far greater than the systematic uncertainties affecting the wavelength scale of either set of observations. Second, in two other high-\( z \) DLAs, toward the radio QSOs Q0454-020 and Q1331+170, the centroids of the 21 cm and metal absorption lines differ by less than 10 km s\(^{-1}\) (Prochaska 1999; Prochaska & Wolfe 1999; see also Lane 2000). While such velocity differences may reflect geometric differences in the sight lines probed by the radio and optical observations—and therefore may offer the means to probe the physical structure of the absorbers on small scales—the 40–50 km s\(^{-1}\) displacement found in Q0201+1120 is surprisingly large, particularly given the compact nature of the radio source. Thus, it seems to us that the redshift mismatch we have uncovered adds to the existing doubts as to the reality of the radio detections; clearly, deeper 21 cm searches would be highly desirable. For the moment, it would appear that a rather high lower limit, \( T_s \approx 4000 \) K, applies to the spin temperature of the H I gas [obtained by scaling the Kanekar & Chengalur 1997 limit to the revised value of \( N(HI) \) we deduce in § 3.1].

We have examined the profiles of the metal absorption lines in Figure 5 for clues to the nature of the absorber. Qualitatively, we do not see clear signs of the “edge leading asymmetry” pattern that, according to Prochaska & Wolfe (1997), is best explained by a sight line through a thick rotating disk. Rather, the kinematics of the gas in this DLA appear to us to be more chaotic, with components of varying strengths distributed over a larger velocity interval than the likely projected rotational speed of a \( \sim L^* \) galaxy. The imaging data do not help in this respect. Galaxy G2, if it is the absorber, is very faint; our observations presumably only pick out the central, high surface brightness region and do not allow us to make meaningful statements as to the overall morphology of this object.

3. ELEMENT ABUNDANCES

In the next stage of the analysis, we deduce ion column densities by fitting the profiles of the absorption lines; this information is then used to estimate the abundances of several elements in the \( z_{abs} = 3.38639 \) DLA.

3.1. Neutral Hydrogen Column Density

Figure 6 shows the profile fit to the damped Ly\( \alpha \) line. The Ly\( \alpha \) forest is very crowded at these redshifts leaving only a relatively few “continuum” windows; consequently, the fit is not as well constrained as is the case for DLAs in lower redshifts. Figure 6 shows the profile fit to the damped Ly\( \alpha \) line. The Ly\( \alpha \) forest is very crowded at these redshifts leaving only a relatively few “continuum” windows; consequently, the fit is not as well constrained as is the case for DLAs in lower redshifts.
redshift QSOs. Our best estimate is \(N(\text{H } \text{i}) = (1.8 \pm 0.3) \times 10^{21} \text{ cm}^{-2}\). Not surprisingly, this value is lower than \(N(\text{H } \text{i}) = 2.5 \times 10^{21} \text{ cm}^{-2}\) deduced by White et al. (1993) from consideration of the line width in their \(\sim 10 \text{ Å}\) resolution spectrum; at these high redshifts, blending with Ly\(z\) forest lines tends to boost the apparent width of a damped line, with the result that the neutral hydrogen column density is easily overestimated.

### 3.2. Metal Lines

Although our HIRES spectrum covers the wavelength region 1026–1573 Å in the rest frame of the DLA, many of the transitions of interest are blended with Ly\(z\) forest lines. We have fitted all the unblended lines (or unblended portions of lines) with Voigt profiles using the VPFIT package.\(^4\) VPFIT determines the Doppler width \(b\), column density \(N\), and redshift \(z\) of individual absorption components by minimizing the difference between observed and computed profiles; the number of components is kept at the minimum required by the S/N of the data.

Oscillator strengths for the transitions considered are from the compilation by Morton (1991) with subsequent revisions as summarized by Tripp, Lu, & Savage (1996). For Ni \(\lambda\lambda1370.1\) and 1454.8, we have used the recent astrophysical and laboratory determinations by Zsargó & Federman (1998) and Fedchak & Lawler (1999). However, the \(f\)-value for one of the Ni \(\pi\) lines in our spectrum, \(\lambda1317.2\), is not among those included in these recent studies. By fitting simultaneously all three Ni \(\pi\) lines in our data with \(f(\lambda1317.2)\) as the free parameter, we deduced \(f(\lambda1317.2) = 0.07\), approximately a factor of 2 lower than the theoretical value listed in the compilation of Morton (1991). This correction is similar to those that Fedchak & Lawler (1999) measured for other Ni \(\pi\) transitions, although data of higher S/N than those considered here are clearly required to refine this astrophysical determination.

From Figure 5 it can be seen that, as well as blending, line saturation limits the number of ion species for which reliable values of the column density can be determined. Specifically, O \(\lambda\lambda302.2\) and C \(\lambda\lambda334.5\) are too strong throughout to be useful for abundance studies. In the case of Si \(\pi\), only \(\lambda\lambda304.4\) is sufficiently weak over part of the velocity range for VPFIT to provide a reliable solution, but the components in question—between 100 and 240 km s\(^{-1}\)—do not constitute the bulk of the absorbing gas. This leaves only N \(\text{i}\), S \(\pi\), Fe \(\pi\), and Ni \(\pi\) as relatively unblended and unsaturated. We found that all the absorption lines of these elements (N \(\text{i}\) \(\lambda\lambda1200.0\) and 1134.7 triplets; S \(\pi\) \(\lambda\lambda253.8\); Fe \(\pi\) \(\lambda\lambda1220.2\) and 1142.4; and Ni \(\pi\) \(\lambda\lambda1454.8, 1370.1,\) and 1317.2) could be fitted satisfactorily with the same set of VPFIT values \((b\) and \(z)\), leaving only the column density \(N\) to vary between the different species. The results are listed in column (2) of Table 3; typical errors returned by the fitting procedure are \(\pm 15\%\).

The fact that for some absorption lines the velocity range 100–240 km s\(^{-1}\) is not covered (see Fig. 5) is not a major concern because the column density in this group of components is less than 5% of the total. As for N \(\text{i}\), although the main components are saturated, we found that the model parameters determined from the weaker unsaturated lines of S \(\pi\), Fe \(\pi\), and Ni \(\pi\) provided the best fit to N \(\text{i}\) as well. The

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\(^{4}\) VPFIT is available at http://www.ast.cam.ac.uk/~rfc/vpfit.html.

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| \(X^i\) | \(\log N(X^i)\) | \(\log N(X^i)/N(H^i)\) | \(\log (X/H)\) | \([X/H]^a\) |
|-------|------------|-----------------|--------------|---------------|
| H\(\text{i}\) | 21.26 | ... | ... | ... |
| N\(\text{i}\) | 15.33 | -5.93 | -4.08 | -1.85 |
| Si\(\text{i}\) | >14.00\(^d\) | ... | ... | ... |
| S\(\text{ii}\) | 15.21 | -6.05 | -4.80 | -1.25 |
| Fe\(\text{ii}\) | 15.35 | -5.91 | -4.50 | -1.41 |
| Ni\(\text{ii}\) | 13.84 | -7.42 | -5.75 | -1.67 |

\(^a\) Log of the column density of ion \(X^i\); typical errors are \(\pm 15\%\).

\(^b\) Solar meteoritic abundance scale from Grevesse & Sauval 1998.

\(^d\) This value refers only to gas in the velocity interval 100–240 km s\(^{-1}\) (relative to \(z_{\text{abs}} = 3.38639\)) which accounts for only a small fraction of the total column density.
4.1. Overabundance of the α-Elements

One of the cornerstones of galactic chemical evolution models is the overabundance of the α-elements relative to Fe seen in Galactic metal-poor stars (where Fe is taken as the measure of metallicity). This effect is generally interpreted as reflecting the delayed production of roughly two-thirds of the iron by Type Ia supernovae (SNe), but in recent years this simple scenario has begun to show its limitations. First, there appear to be real differences between different elements within the α-capture group (e.g., Chen et al. 2000; Prochaska et al. 2000). The most obvious of these is the finding that the ratio [O/Fe] shows a steady increase with decreasing [Fe/H] and reaches [O/Fe] ~ +1.0 at [Fe/H] ~ −3. In contrast, most (but not all—see below) of the other α-elements seem to have a constant [Z/Fe] ~ +0.5 between [Fe/H] ~ −1 and −3 (Takeda et al. 2001 and references therein). Second, since the progenitors of Type Ia supernovae have yet to be positively identified, the timescale for the release of Fe is uncertain (see, for example, the comprehensive review by Nomoto et al. 2000). It is customary to assume a ~1 Gyr delay between the production of O and other α-elements in Type II SNe on the one hand and the release of the bulk of the Fe-peak elements by Type Ia SNe on the other, but it is possible that the latter follow the former on much shorter intervals. For example, Regős et al. (2001) have recently pointed out that the peak in the rate of Type Ia SNe formed by the edge-lit detonation of CO white dwarfs is reached less than 200 Myr after the onset of star formation. This would reduce drastically the evolutionary timescales implied by the α-element overabundances in halo and thick disk stars of the Milky Way.

Returning to the z_{abs} = 3.38639 DLA, the only α-element we cover in our spectrum is sulphur. Its behavior at low [Fe/H] is not as well documented as that of other α-elements because the sulphur abundance is determined from only one high-excitation line in the far red (S λ 28694). The studies by François (1988) and most recently Takeda et al. (2001) found S to track O, while Prochaska et al. (2000) found a large scatter about [S/Fe] ~ 0 (i.e., no enhancement of sulphur) in thick disk stars with [Fe/H] = −0.4 to −0.6. All of these authors stress the importance of carrying out more extensive surveys of the abundance of sulphur in the future.

From the last column of Table 3, it can be seen that we find [S/Fe] ~ +0.16 at [Fe/H] = −1.41. This represents at most a mild S overabundance, given our error of ±0.1 in the log of the ratio of any two elements and the possibility that Fe, unlike S, may be partly depleted onto dust. For comparison, François (1988) finds [S/Fe] ~ +0.6 in Milky Way stars with [Fe/H] = −1.4. In the context of the discussion above, we would conclude that there has been sufficient time, since the last episode of star formation that enriched this damped Lyz system in metals, for Fe to build up to a near-solar value relative to S. The lack of a pronounced enhancement of the α-elements now seems common to many low-metallicity DLMs (e.g., Centurión et al. 2000; Pettini et al. 2000) and has been interpreted as evidence for generally low rates of star formation.

4.2. N/α

Nitrogen is another element at our disposal that may be used to date the chemical enrichment process. At low metallicities the main source of N is thought to be primary nucleosynthesis in intermediate-mass stars (2–5 M_{⊙}) with a time delay of 250–500 Myr relative to the near-instantaneous release of O after a burst of star formation (Henry, Edmunds, & Köppen 2000; Lattanzio et al. 2001). The [N/α] ratio in DLMs exhibits a much larger scatter than any other element ratio not involving N (Lu, Sargent, & Barlow 1998; Centurión et al. 1998), with values spanning the range between secondary and primary nitrogen production. Pettini, Lipman, & Hunstead (1995) proposed that this scatter is most naturally explained as the result of the delayed release of primary N, although there are dissenting viewpoints (Izotov & Thuan 1999).

From column (5) of Table 3 it can be seen that in the z_{abs} = 3.38639 DLA we find N to be less abundant than S by a factor of 4, that is, [N/S] = −0.6. With the assumption that [S/O] = 0, this corresponds to (N/O) = −1.51 at (O/H) + 12 = 7.58. Referring to Figure 5 of Pettini et al. (1995), it can be seen that (N/O) = −1.51 is a “high” value, in the sense that it is close to that expected following the release of primary nitrogen. It is at the upper end of the range measured in DLMs and in good agreement with the typical (N/O) in blue compact and H II galaxies with (O/H) + 12 ≈ 7.6 (e.g., Fig. 1b of Henry et al. 2000).

In concluding this section, it would seem that, within the current understanding of their time evolution, both the [Z/Fe] and the [N/α] ratios measured in this DLA to the last major episode of metal enrichment having occurred several hundred Myr prior to the redshift at which we observe the DLA. Adopting 500 Myr as the time lag for both N and Fe production places the last major episode of star formation in this galaxy at z > 4.3 (H_{0} = 65 km s^{-1} Mpc^{-1}). This conclusion is not at odds with what we already know about star formation at high redshifts, given that there seems to be no change in the luminosity function of star-forming galaxies between z = 3 and 4.5 (Steidel et al. 1999) and that many LBGs have stellar populations older than 500 Myr (Shapley et al. 2001, in preparation).

As emphasized above, this type of analysis is based on many assumptions whose validity remains to be verified; ultimately it will only be possible to establish whether element ratios give a self-consistent picture by conducting a full study of a large body of high-quality measurements. However, we note that at least one other well-studied high-α DLA has similar chemical properties to those deduced here. From Very Large Telescope (VLT)/UVES observations of the z_{abs} = 3.3901 DLA in Q0000−2620, Molaro et al. (2000) deduce [α/Fe-peak] ~ +0.2 and (N/O) = −1.69 at (O/H) + 12 = 7.01. Thus, this may well be another example of a DLA galaxy with low, or episodic, star formation that started before z = 4.3.

5. SUMMARY AND CONCLUSIONS

In this paper we have presented imaging and spectroscopic observations aimed primarily at investigating the nature of the absorber giving rise to the strong damped Lyz system at z_{abs} = 3.38639 in front of Q0201+1120. Our main findings can be summarized as follows:

5 We apologize to the reader for this sudden change of notation, but nearly all published measurements of the N and O abundances are in these units. (N/O) and (O/H) are the logarithmic values of the element ratios by number, without reference to the solar values.
1. The DLA is a part of a concentration of matter that includes at least four galaxies at \( z \approx 3.37 \) over transverse dimensions of at least 5 h\(^{-1}\) Mpc (comoving). Two of the galaxies are seen directly via their UV stellar continua, while two others (including the DLA) are detected in absorption against higher redshift sources. Since we have so far obtained spectra for only about one-quarter of the \( U \) drop candidates in this field, it is likely that the structure includes other objects at \( z \approx 3.37 \).

2. We have found a promising candidate for the absorber in a photometric Lyman break object (galaxy G2) only 2.9′ away from the QSO sight line. If confirmed by future spectroscopy to be at the absorption redshift, then the galaxy associated with this DLA has a UV luminosity of about 0.7\( L^* \) and a linear extent of at least 15 h\(^{-1}\) kpc. Otherwise, the absorber is likely to be fainter than about 0.4\( L^* \).

3. The H\(^\alpha\) gas producing the damped system is highly turbulent, with a spin temperature \( T_s \gtrsim 4000 \) K and complex absorption-line profiles, consisting of many discrete components spanning \( \sim 270 \) km s\(^{-1}\). Neither is what one may have expected from a cold, rotationally supported disk.

4. The DLA has a metallicity \( Z \approx 1/20 Z_\odot \), at the upper end of the distribution of values of \( Z_{\text{DLM}} \) at these redshifts but lower than those deduced for other luminous Lyman break galaxies, although the data here are still very sparse. Further, it exhibits no marked overabundance of the \( \alpha \)-elements (in this case S) relative to Fe and a relatively high (N/\alpha) ratio for its low metallicity. Both element ratios can be understood if there has been a relatively quiescent interval, lasting more than \( \sim 500 \) Myr, since the last major burst of star formation in this galaxy, allowing the delayed release of Fe from Type Ia SNe and of N from asymptotic giant branch stars of intermediate mass. If this reasoning is correct, the star formation episode responsible for producing the heavy elements we see occurred at \( z \gtrsim 4.3 \). The chemical properties of this absorber are similar to those of another high-z DLA, at \( z_{\text{abs}} = 3.901 \) in Q0000\(-262\), which has been extensively studied with both the Keck and VLT echelle spectrographs.

Firm conclusions about the nature of DLAs at high redshifts are hampered by the lack of follow-up spectroscopy of galaxy G2. If this is indeed the absorber, it would be only the second case where a high-z DLA has been identified with a Lyman break galaxy, after the \( z_{\text{abs}} = 3.151 \) system in Q2233 + 1310 (Steidel, Pettini, & Hamilton 1995; Djorgovski et al. 1996), although others have been detected in Ly\(\alpha\) emission (e.g., Fynbo, Burud, & Møller 2000 and references therein). In general, our deep Lyman break imaging has shown that the galaxies producing DLAs at \( z \gtrsim 3 \) must be significantly sub-\( L^* \) in their stellar continua (e.g., Steidel et al. 1995, 1998) and that detections such as this one are the exception rather than the rule.

We conclude that, although the statistics are still very limited, DLAs seem to sample a wide range of the luminosity function of galaxies at \( z \gtrsim 3 \). QSO absorption-line spectroscopy still gives us the most precise measurements of many important physical properties of high-redshift gas. However, only by combining it with deep imaging will it be possible to realize its full potential for unraveling the nature and evolution of galaxies at early times.

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