CHEMICAL EVOLUTION OF DAMPED Lyα GALAXIES: THE [S/Zn] ABUNDANCE RATIO AT REDSHIFT $\geq 2$

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ABSTRACT

Relative elemental abundances, and in particular the $\alpha$/Fe ratio, are important diagnostic tools of the chemical evolution of damped Lyα (DLA) systems. The S/Zn ratio is not affected by differential dust depletion and is an excellent estimator of the $\alpha$/Fe ratio. We report six new determinations of sulphur abundance in DLA systems at $z_{\text{abs}} \geq 2$ with already-known zinc abundances. The combination with extant data from the literature provides a measure of the S/Zn abundance ratio for a total of 11 high-redshift DLA systems. The observed [S/Zn] ratios do not show the characteristic [$\alpha$/Fe] enhancement observed in metal-poor stars of the Milky Way at a comparable level of metallicity ([Zn/H] $\approx -1$). The behavior of DLA data is consistent with a general trend of a decreasing [S/Zn] ratio with increasing metallicity [Zn/H]. This would be the first evidence of the expected decrease of the $\alpha$/Fe ratio in the course of the chemical evolution of DLA systems. However, in contrast to what is observed in our Galaxy, the $\alpha$/iron peak ratio seems to attain solar values when the metallicity is still low ([Zn/H] $\leq -1$) and to decrease below solar values at higher metallicities. The behavior of the $\alpha$/Fe ratio challenges the frequently adopted hypothesis that high-redshift DLA systems are progenitors of spiral galaxies and instead favors an origin in galaxies characterized by low star formation rates, in agreement with the results from imaging studies of low-redshift DLA systems, where the candidate DLA galaxies show a variety of morphological types, including dwarf and low surface brightness galaxies and only a minority of spirals.

Subject headings: cosmology: observations — galaxies: abundances — galaxies: evolution — quasars: absorption lines

1. INTRODUCTION

Damped Lyα (DLA) systems are quasi-stellar object (QSO) absorbers with the highest values of neutral hydrogen column density [log $N$(H i) $\geq 20.3$ atoms cm$^{-2}$]. The Lyα absorption profiles show extended “radiation damping” wings (hence their name) and are always associated with narrow metal absorptions. Even though it is generally accepted that DLA absorbers at high redshifts originate in protogalaxies located in the direction of the background QSO, the nature of such intervening galaxies is still a subject of debate.

The analysis of the kinematics of the metal lines has suggested that DLA systems arise in massive rotating disks which are the progenitors of the present-day spiral galaxies (Wolfe et al. 1995; Prochaska & Wolfe 1997, 1999). However, other works indicate that the observed kinematical properties can be equally explained by low-mass protogalactic objects (Haehnelt, Steinmetz, & Rauch 1998; Ledoux et al. 1998).

The imaging of galaxies in the field of the background QSOs indicates that at $z_{\text{abs}} \leq 1$—where this technique can be applied—the population of DLA galaxies is not dominated by a specific morphological type, and, in particular, spirals constitute a small fraction of the sample (Le Brun et al. 1997; Rao & Turnshek 1998).

Abundance studies of DLA systems also have the potential to provide independent clues to understanding the nature of this class of QSO absorbers. Abundance determinations have already been obtained for about 60 systems, mainly at $z_{\text{abs}} > 1.7$, (Lu et al. 1996; Pettini et al. 1997, 1999; Prochaska & Wolfe 1999, hereafter PW99). DLA galaxies show low metallicities—typically 10% of solar—comparable with the metallicity level measured in metal-poor stars of the Galactic halo. Although the precision obtained in DLA galaxies’ abundance determinations is remarkable and often comparable to that attained in the Galactic interstellar medium (ISM), the interpretation of the observed abundance ratios has led to contradictory conclusions.

If DLA galaxies are protospirals and have experienced a chemical evolution similar to that of our Galaxy, we expect to observe the elemental abundance pattern typical of halo stars of comparable metallicity. In particular, we expect to observe the enhancement of the $\alpha$-elements to iron peak elements ratio$^1$ [$\alpha$/Fe] $\approx 0.5$ characteristic of Galactic metal-poor stars (Ryan, Norris, & Beers 1996). The only [$\alpha$/Fe] ratio with a large number of determinations in DLA systems is [Si/Fe]. The mean value $\langle$[Si/Fe]$\rangle \approx 0.4 \pm 0.2$ is consistent with the typical value of the Galactic halo stars and has been interpreted as evidence for an origin of DLA systems in protospirals (Lu et al. 1996; PW99). However, also in the nearby ISM one typically finds $\langle$[Si/Fe]$\rangle \approx 0.4$ owing to differential elemental depletion onto dust grains (Savage & Sembach 1996). Vladilo (1998) obtained intrinsic solar ratios ([Si/Fe] $\approx 0$) in DLA systems after correction for the differential elemental depletion. Also, Pettini et al. (1999) have recently found solar Si/Zn ratios in three DLA systems by taking into account dust effects.

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$^1$ Based on observations made with the William Herschel telescope operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de Los Muchachos of the Instituto de Astrofísica de Canarias and on observations collected with the ESO 3.6 m telescope at the European Southern Observatory, Chile.

$^2$ Using the standard definition $[X/Y] = \log (X/Y) - \log (X/Y)_\odot$.  

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By using ratios of undepleted elements such as [S/Zn], Molaro et al. (1996) and Molaro, Centurión, & Vladilo (1998, hereafter MCV98) also obtained solar ratios, in spite of the low metallicity of the DLA systems investigated. Since sulphur and zinc are essentially undepleted in the ISM, the [S/Zn] ratio is probably the best diagnostic of the [S/Fe] ratio available for DLA systems. However, only a few measurements of sulphur abundances are available owing to the difficulty of observing the S II resonant triplet in the Lyα forest. For this reason we have performed a search for S II in DLA systems. Here we present the results of this search in seven DLA systems with known Zn II abundances. We obtain three sulphur abundance measurements and three limits, which allow us to enlarge significantly the sample of [S/Zn] determinations.

2. Observations and Data Reduction

The QSOs observed in the course of the present investigation are listed in Table 1, together with relevant information concerning the observations. The spectra of QSO 0013—004 and QSO 2231—0015 were obtained with the Cassegrain echelle spectrograph (CASPEC) at the Cassegrain focus of the ESO 3.6 m telescope at La Silla, Chile. The spectra of the remaining QSOs were obtained with the two arms ISIS spectrograph at the Cassegrain focus of the William Herschell Telescope (WHT, 4.2 m) at La Palma, Canary Islands.

For the CASPEC observations we used the echelle grating of 31.6 grooves mm⁻¹ and a Tektronix CCD with 1024 × 1024 square pixels of 24 μm in size. The CCD was binned at a step of 2 pixels along the dispersion direction and the slit width was set at 2.1 in order to have the projection onto 2 binned pixels of the detector. The slit width matched the seeing, which was around 2″ during the observations at La Silla.

For the observations performed with the ISIS blue arm we used a 1200 grooves mm⁻¹ grating coupled with an EEV CCD with 2048 × 4200 square pixels of 13.5 μm in size. The CCD was binned in the spatial and dispersion directions at steps of 2 × 2 pixels. The slit width was set at 1″. This value still allows a correct sampling of the spectrum without any loss in resolution thanks to the small pixel size of the EEV CCD.

The FWHM of the instrumental profile sampled with 2 binned pixels, Δλ_{inst}, was measured from the emission lines of the thorium-argon lamp (CASPEC) and from the copper-argon plus copper-neon lamps (ISIS blue arm) recorded contiguously to each target exposure. The resulting resolving power R = λ/Δλ_{inst} was R = 19,000 for CASPEC spectra and ≈5000 in the sulphur region of ISIS blue data, corresponding to a velocity resolution of Δv ≈ 16 km s⁻¹ and 60 km s⁻¹, respectively.

The data reduction was performed using the ECHELLE (CASPEC spectra) and LONG (ISIS spectra) routines implemented in the software package MIDAS developed at ESO. The first steps of the reduction procedure—including flat-fielding, cosmic-ray removal, sky subtraction, optimal extraction, and wavelength calibration—were performed separately on the different spectra of each QSO. Typical internal errors in the wavelength calibrations are ≈4 mÅ for CASPEC spectra and ≈30 mÅ for ISIS blue data.

The observed wavelength scale of the spectra was then transformed into a vacuum, heliocentric wavelength scale. At this point the different spectra of each QSO were averaged, using as weights the continuum levels of the exposures. Finally, for each spectral range under study, the local continuum was determined in the average spectrum by using a spline to smoothly connect the regions free from absorption features. The final spectrum used for the analysis was obtained by normalizing the average spectrum to these continua. The signal-to-noise ratios (S/Ns) per pixel of the extracted final spectra, estimated from the rms scatter of the continuum near the absorptions under study, are typically in the range 10–25.

In addition to the S II triplet at 1254 Å, our data also cover, in general, the spectral regions of N I multiplets (at 1134 and 1200 Å) and the transitions of O I (at 1302 and 1355 Å), Si II (at 1190, 1193, 1260, 1304, and 1526 Å), and Fe II (at 1121, 1125, 1127, 1133, 1143, and 1144 Å). In this paper we focus our attention on the new measurements of the S II triplet. When possible, we used other lines to obtain information that could be used to constrain the S II column densities. We do not report O I column densities because the transition at 1302 Å is heavily saturated, while the extremely weak O I λ1356 line is not detected and provides no stringent upper limits. Nitrogen abundance determinations in these DLA systems will be discussed in a subsequent paper.

3. Column Densities

Column densities have been obtained by fitting theoretical Voigt profiles to the observed absorption lines via χ²

| QSO     | V     | z_{em} | z_{abs} | Telescope | Date       | t_{exp} (s) | Number of Spectra | Coverage (Å) |
|---------|-------|--------|---------|-----------|------------|-------------|-------------------|--------------|
| 0013 — 004 ...... | 18.2  | 2.084  | 1.9730  | ESO 3.6 m | 1997 Sep 4 | 13,500      | 2                 | 3661–4638    |
|         |       |        |         |           | 1997 Sep 5 | 14,400      | 2                 | 3431–4366    |
|         |       |        |         |           | 1997 Sep 6 | 14,400      | 2                 | 3710–4643    |
| 0149 + 335 ...... | 18.5  | 2.431  | 2.1408  | WHT       | 1998 Dec 21| 3600        | 2                 | 3350–4190    |
| 0841 + 129 ...... | 17.0  | 2.5    | 2.3745  | WHT       | 1998 Dec 21| 3600        | 2                 | 3710–4643    |
|         |       |        |         |           | 1998 Dec 23| 4000        | 2                 | 3710–4643    |
| 1215 + 333 ...... | 17.5  | 2.606  | 1.999   | WHT       | 1998 Dec 22| 3560        | 2                 | 3710–4643    |
|         |       |        |         |           | 1998 Dec 24| 3600        | 2                 | 3710–4643    |
| 1223 + 178 ...... | 18.1  | 2.936  | 2.4658  | WHT       | 1998 Dec 24| 3600        | 2                 | 3880–4775    |
| 2231 — 0015 ...... | 17.4  | 3.020  | 2.0662  | ESO 3.6 m | 1997 Sep 5 | 7200        | 1                 | 3661–4638    |
|         |       |        |         |           | 1997 Sep 6 | 7200        | 1                 | 3661–4638    |
minimization. This step was performed using
the FITLYMAN routines (Fontana & Ballester 1995)
included in the MIDAS package. During the fitting
procedure the theoretical profiles were convolved
with the instrumental point-spread function modeled
from the analysis of the emission lines of the arcs.
Portions of the profiles contaminated by intervening Lyα
absorbers were excluded from the fit.

The FITLYMAN routines determine the redshift, the
 column density (atoms cm$^{-2}$), and the broadening para-
meter ($b$-value)$^3$ of the absorption components, as well
as the fit errors for each one of these quantities. In ad-
dition, we estimated errors due to the uncertainty in the continuum
placement, as we explain in the rest of this section.

Measurements of S II column densities were derived from
the three lines at 1250.584, 1253.811, and 1259.519 Å
with oscillator strengths $f_j = 0.00545$, 0.01088, and 0.01624,
respectively. All the atomic data used in this work are from
Morton (1991). The S II triplet is generally unsaturated but
can be contaminated by the Ly$\alpha$ forest, and we have been
able to measure the sulphur column density in only four out
of the seven DLA systems under study.

In Table 2 we give our derived S II column densities and
$b$-values. No sulphur abundance has been previously
reported for the DLA systems under study. We now
comment briefly on the column density measurements of
each DLA system, starting with the two observed at higher
spectral resolution (CASPEC data). For the ISIS data, we
first discuss those for which a determination of S II
column densities was possible.

3.1. System at $z_{abs} = 1.9730$ toward QSO 0013$-$004

For this absorber we derived the S II column density from
the fit to the $\lambda 1253$ transition. The bluest transition at 1250
Å—the weakest one of the triplet—is quite noisy since it is
located in the first order of the echellogram where the S/N is
low. The reddest transition at 1259 Å is completely blended,
as one can see in Figure 1a. We remark that the S II $\lambda 1253$
line is found at exactly the same redshift ($z_{abs} = 1.9730$) as
the Zn II and Cr II absorptions studied by Pettini et al.
(1994). The $\lambda 1250$ transition, in spite of the low S/N, is very
well matched by the synthetic spectrum built with this red-
shift value (Fig. 1a, solid line).

Our best fit to the S II $\lambda 1253$ absorption gives log
$N$(S II) = 14.86 and $b = 24.5$ km s$^{-1}$. The rest-frame equi-
valent width of the same line, $EW_{rest} = 81$ mA, yields log
$N$(S II) = 14.74 by using the linear part of the curve of
growth (COG), which is indicative within the errors of a
linear regime. In fact, we obtained an acceptable fit to the S
II $\lambda 1253$ absorption for a wide range of $b$-values, $b = 14$ and
$b = 35$ being the extreme values, and in both cases the
resulting S II column density is consistent with the best-fit
value within the errors. We explored the uncertainty in the
column density coming from the continuum tracing by
shifting the continuum $\pm 1$ rms and repeating the fit in each
case. We obtained the best fits for log $N$(S II) = 14.77
($b = 20.4$) and log $N$(S II) = 14.91 ($b = 24.6$) for the lower
and upper continuum, respectively. We adopt log $N$(S II)
= 14.86 ($\pm 0.12$) and $b = 24.5$ ($\pm 10$), given in Table 2,
which takes into account the largest excursion of the S II
column density values.

Unfortunately, the Si II transitions available in our spec-
trum ($\lambda \lambda 1260$, 1304, and 1526 ) are saturated or blended,
making a determination of the Si II column density for this
system impossible.

3.2. System at $z_{abs} = 2.0662$ toward QSO 2231$-$0015

Only S II $\lambda 1253$ absorption is available in this DLA
system, since the other two transitions of the triplet are
contaminated by the Ly$\alpha$ forest (see Fig. 1, upper panel).

TABLE 2

| QSO      | $z_{abs}$ | log $N$(S II) | $b$  | Reference | log $N$(Zn II) | Reference | log $N$(H I) | Reference |
|----------|-----------|---------------|------|-----------|---------------|-----------|--------------|-----------|
| 0013$-$004| 1.9730    | 14.86 $\pm$ 0.12 | 24.5 $\pm$ 10 | 1 | 12.63 $\pm$ 0.06 | 2 | 20.70 $\pm$ 0.05 | 3 |
| 0149 + 3335| 2.1408    | $<$ 14.80     | ... | 1 | 11.50 $\pm$ 0.10 | 4 | 20.50 $\pm$ 0.10 | 4 |
| 0841 + 129  | 2.3745    | 14.92 $^{+0.16}_{-0.21}$ | 20 $\pm$ 3$^a$ | 1 | 12.12 $\pm$ 0.05 | 4 | 20.96 $\pm$ 0.10 | 1 |
| 0841 + 129  | 2.4762    | 14.81 $\pm$ 0.21 | 13.5 $\pm$ 2 | 1 | $<$ 11.78 | 4 | 20.76 $\pm$ 0.10 | 1 |
| 1215 + 333  | 1.999     | $<$ 15.36     | 18$-$70 | 1 | 12.29 $\pm$ 0.06 | 4 | 20.95 $\pm$ 0.07 | 2 |
| 2231$-$0015| 2.0662    | $>$ 14.90     | ... | 1 | 12.46 $\pm$ 0.02 | 4 | 20.56 $\pm$ 0.10 | 4 |

$^a$ From the fit to the Fe II transitions at 1121, 1125, 1127, 1133, 1143, and 1144 Å.

$^b$ Limit obtained by using the linear part of the COG, since no information is available on the $b$-value (see text for details).

REFERENCES.—(1) This paper; (2) Pettini et al. 1994; (3) Ge & Betchold 1997; (4) PW99.
The fitted $\text{S} \Pi \lambda 1253$ line is observed at the same redshift ($z_{\text{abs}} = 2.0662$) as found by Lu et al. (1996) and PW99 in their studies of this system. Moreover, part of our wavelength range is also covered in the spectrum of PW99, and features in both spectra like O I $\lambda 1302$ and $\text{S} \Pi \lambda 1304$ occur also at the same velocity position.

The $\text{S} \Pi$ absorption presents a high degree of saturation, and only with an independent estimation of the $b$-value would it be possible to obtain a reliable estimate of the $\text{S} \Pi$ column density. Unfortunately, no information is available on the $b$-value for this DLA system, since abundances before this work have been obtained by using the opacity method. The Ni $\Pi$ ($\lambda 1370$) and $\text{C} \Pi$ ($\lambda 1335$) absorptions observed in the higher S/N spectrum of PW99 are not detected in our spectrum, making it impossible to constrain the $b$-parameter in this system. We estimated log $N(\text{S} \Pi) > 14.90$, a lower limit obtained by using the rest-frame equivalent width and the linear part of the COG.

3.3. System at $z_{\text{abs}} = 2.3745$ toward QSO 0841 + 129

This is the brightest target observed. The spectrum of this BL Lac object discovered by C. Hazard shows two DLA systems previously analyzed by Pettini et al. (1997) and shown in Figure 2a. Our best fit to the lower redshift damped absorption at $z_{\text{abs}} = 2.374$ gives log $N(\text{H} \text{I}) = 20.96 \pm 0.10$, in perfect agreement with log $N(\text{H} \text{I}) = 20.95 \pm 0.10$, the value reported by Pettini et al. (1997).

For this $z_{\text{abs}} = 2.3745$ system a feature at $4 \sigma$ significance level is observed at the expected redshifted position of the strongest triplet transition $\text{S} \Pi \lambda 1259$ (Fig. 2b, vertical arrow). The blue ISIS spectrum of Pettini et al. (1997, see their Fig. 2), recorded at about half of our resolution, also shows this feature, indicating that it is real.

The $\text{S} \Pi \lambda 1259$ transition is observed in the red wing of the higher redshift DLA absorption at $z_{\text{abs}} = 2.476$, which unfortunately precludes the detection of the other two bluer absorptions of the $\text{S} \Pi$ triplet. Our best fit to this damped absorption ($z_{\text{abs}} = 2.476$), shown with solid and dotted lines in Figures 2a and 2b, gives log $N(\text{H} \text{I}) = 20.83 \pm 0.10$, in good agreement with log $N(\text{H} \text{I}) = 20.79 \pm 0.10$, reported by Pettini et al. (1997). We renormalized this portion of the spectrum to the Ly$\alpha$ profile before fitting the $\text{S} \Pi$ line. For this system there is no independent information on the $b$-value from the literature. In order to constrain the $\text{S} \Pi$ column density, we estimated the $b$-value in this line of sight from the analysis of the Fe $\text{II}$ transitions at 1121, 1125, 1127, 1133, 1143, and 1144 $\AA$. We obtained log $N(\text{Fe} \text{II}) = 14.83 \pm 0.15$ and $b = 20 \pm 3 \text{ km s}^{-1}$ (see Fig. 2c). The errors in the Fe $\text{II}$ column density and $b$-value take into account the fit errors and the error due to the uncertainty of the continuum truncation.

By fixing $b(\text{S} \Pi) = b(\text{Fe} \text{II}) = 20 \text{ km s}^{-1}$ and $z_{\text{abs}} = 2.3745$—at which we observe six Fe $\text{II}$ absorptions—in the $\text{S} \Pi$ fitting procedure we obtained log $N(\text{S} \Pi) = 14.92 \pm 0.09$. In Figure 3a this fit is shown with a solid line overimposed to the spectrum renormalized to the Ly$\alpha$ absorption. Changing the $b$-value by $\pm 3 \text{ km s}^{-1}$ affects the $\text{S} \Pi$ column density only by $\pm 0.02$ dex. Moreover, if we use $b = 13 \text{ km s}^{-1}$ obtained from the analysis of the N I $\lambda 1134$ and $\lambda 1200$ multiplets, we obtain log $N(\text{S} \Pi) = 14.89 \pm 0.14$, which is still consistent with the column density obtained for $b = 20 \text{ km s}^{-1}$. These results clearly indicate that the $\text{S} \Pi$ absorption under study is unsaturated, and this is reinforced by the fact that by using the rest equivalent width ($\text{EW}_{\text{rest}} = 175 \text{ mÅ}$) over the linear part of the COG we again obtained log $N(\text{S} \Pi) = 14.89$. We estimated the error due to the continuum placement by fitting the $\text{S} \Pi$ absorption in the spectra normalized to the local continua shown with dotted lines in Figure 2a, and we obtained $\sigma_{\text{log N(S} \Pi)} = 0.16$. This error dominates the error budget, and we adopted log $N(\text{S} \Pi) = 14.92^{+0.19}_{-0.11}$. We remark that in case we consider the $\text{S} \Pi$ absorption nondetected, we can use log $N(\text{S} \Pi) < 14.92$ as a conservative $4 \sigma$ upper limit. Even in this case, the result would not affect the main conclusion of the present work, as we discuss in § 4. Nevertheless, as it has been explained above, there are at least three good reasons which make this detection reliable: (i) the feature seems to be present also in the spectrum of Pettini et al. (1997); (ii) the feature is observed at $z_{\text{abs}} = 2.3745$, the same redshift at which we observed six single-component transitions of Fe $\text{II}$ shown in Figure 2c; and (iii) the single-component structure and the redshift are confirmed by the absorptions of $\text{S} \Pi \lambda 1808$, Cr $\Pi \lambda 2056$, 2062, 2066, and Zn $\Pi \lambda 2062$ observed in the higher resolution and S/N High-Resolution Echelle Spectrograph–Keck spectrum of PW99.

3.4. System at $z_{\text{abs}} = 2.4762$ toward QSO 0841 + 129

As can be seen in Figures 2a and 2b, the $\text{S} \Pi$ triplet of this system is overimposed to a smooth, broad absorption which is also seen in the spectrum of Pettini et al. (1997). We investigated the possibility that this broad absorption may be due to Ly$\alpha$ line locking with the velocity separation of C $\text{IV}$ or Si $\text{IV}$ resonance doublets, since this process is associated with absorption systems at $z_{\text{abs}} \approx z_{\text{em}}$ of the QSO (Srianand 2000). This is the case here, since $z_{\text{em}} \approx 2.5$ has been estimated from the onset of the Ly$\alpha$ forest (Pettini et al. 1997). However, from the line-locking process one would expect a velocity separation between the broad profile and the $z_{\text{abs}} = 2.4762$ Ly$\alpha$ absorptions correspondent to the velocity separation between the two lines of the C $\text{IV}$ or Si $\text{IV}$ doublet of that system. This is not the case here, at least for the C $\text{IV}$ or Si $\text{IV}$ doublets. In any case, the presence of the broad feature does not affect our measurements because the $\text{S} \Pi$ absorptions are thin, as expected for DLA metal lines, and are clearly distinguishable from the broad feature. In order to analyze the $\text{S} \Pi$ triplet, we renormalized this portion of the spectrum to the broad profile shown in Figure 2b. The $\text{S} \Pi \lambda 1253$ transition is heavily blended, and we excluded this feature from the fitting procedure. Our best fit to the $\text{S} \Pi \lambda 1250$ and $\lambda 1259$ transitions gives log $N(\text{S} \Pi) = 14.81, b = 13.5 \text{ km s}^{-1}$, and $z_{\text{abs}} = 2.4762$. In Figure 3b we show the synthetic spectrum of the $\text{S} \Pi$ triplet computed with these parameters. We remark that redshift obtained from the $\text{S} \Pi$ triplet is in perfect agreement with the one found by PW99 for different single-component metal absorptions observed in their Keck spectrum and hence enhances the reliability of the $\text{S} \Pi$ detections. Pettini et al. (1999) gave $z_{\text{abs}} = 2.4764$ for this system, but this value was obtained just from the fit to the wide DLA absorption.

By using the rest equivalent width ($\text{EW}_{\text{rest}} = 48 \text{ mÅ}$) of the weakest $\lambda 1250$ transition over the linear part of the COG, we obtained essentially the same column density, log $N(\text{S} \Pi) = 14.80$, indicating that this transition is not saturated. Again, the major uncertainty in the column density comes from the continuum placement. We renormalized the spectra to the upper and lower continua shown with dotted lines in Figure 2b, and we measured for $\text{S} \Pi \lambda 1250$ absorption $\text{EW}_{\text{rest}} = 70$ and 30 mÅ, which yield
Fig. 2.—Normalized portions of the ISIS blue spectra of QSO 0841+129 and QSO 1215+333. (a) The two DLA systems toward QSO 0841+129. Solid and dotted lines show the synthetic damping profiles corresponding to the column density of neutral hydrogen given in Table 1. (b) S II λ1259 transition of the \( z_{\text{abs}} = 2.3745 \) DLA system and S II triplet of the \( z_{\text{abs}} = 2.4762 \) DLA system toward QSO 0841+129. The left single arrow indicates the position of S II 1259 at \( z_{\text{abs}} = 2.3745 \), obtained from the six Fe II absorptions and in perfect agreement with the value given by PW99. The three arrows on the right side are plotted at the redshifted position of the S II triplet for the DLA system at \( z_{\text{abs}} = 2.4762 \). Solid and dotted lines show the damped profile and the continua to which this portion of the spectra have been renormalized in order to measure the S II column densities in both DLA systems. (c) Fe II lines of the \( z_{\text{abs}} = 2.3745 \) DLA system in the normalized spectrum of QSO 0841+129. Solid lines show the synthetic spectrum obtained from the fit of all the Fe II absorptions contemporaneously. (d) Normalized portion of the QSO 1215+333 spectrum in the region of the DLA absorption and S II triplet. The solid and dotted lines are the continua to which the spectrum have been renormalized in order to analyze the S II absorptions.

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\log N(\text{S II}) = 14.96 \text{ and } 14.60 \text{ atoms cm}^{-2}, \text{ respectively.}\]

We adopted \( \log N(\text{S II}) = 14.81^{+0.15}_{-0.21} \) given in Table 2.

3.5. System at \( z_{\text{abs}} = 1.999 \) toward QSO 1215+333

Also in this system, the S II triplet is observed overimposed on a wide absorption (see Fig. 2d). In this case, an origin in the line-locking process is unlikely because there is a significant difference between \( z_{\text{abs}} \) and \( z_{\text{em}} \) (see Table 1). To analyze the S II triplet we have renormalized this portion of the spectrum to the broad absorption (Fig. 3c). The S II λ1253 transition, although partially blended, is the only feature that can be used to derive the column density.
The S II \( \lambda 1259 \) transition is heavily blended, and our best fit to the S II \( \lambda 1253 \) line gives \( \log N(S\ II) = 15.11 \) for \( b = 55 \) km s\(^{-1}\). A synthetic S II spectrum built with these values is shown with a solid line overimposed to the observed spectrum in Figure 3c. In order to explore the degree of saturation of this absorption, we performed the fit for a large range of \( b \)-values. We obtained \( b = 70 \) km s\(^{-1}\) [\( \log N(S\ II) = 14.99 \)] and \( b = 18 \) km s\(^{-1}\) [\( \log N(S\ II) = 15.23 \)], the maximum and minimum \( b \)-values that can give an acceptable fit to the observed profile. Again, the column density does not depend very much on the \( b \)-value, indicating a low degree of saturation.

In order to estimate this error, we renormalized the spectrum to the continuum positions shown with dotted lines in Figure 2d. With the upper continuum we obtained a minimum \( b = 15 \) km s\(^{-1}\) for which an acceptable fit can be obtained, yielding \( \log N(S\ II) = 15.36 \). In this case the \( \lambda 1253 \) line presents a certain degree of saturation since the rest equivalent width over the linear part of the COG gives \( \log N(S\ II) = 15.10 \). For the lower continuum the column density does not depend on the \( b \)-value, and we obtained \( \log N(S\ II) = 15.00 \) \( ^{+0.02} \) for \( 18 \) km s\(^{-1}\) \( ^{<} \) \( b \) \( ^{<} \) 50 km s\(^{-1}\). We therefore obtain for this system \( \log N(S\ II) = 15.11 \) \( ^{+0.25} \) \( ^{-0.12} \).

Nevertheless, since this determination relies on just one absorption which is partially blended and no other single metal absorptions are available in our spectrum to confirm the redshift, we adopt the most conservative result by considering the sulphur abundance as an upper limit, \( \log N(S\ II) = 15.11 \) \( ^{+0.25} \) \( ^{-0.12} \).

3.6. System at \( z_{\text{abs}} = 2.1408 \) toward QSO 0149 + 335

None of the three absorptions of the S II triplet are detected. Their expected redshifted positions are marked with dashed vertical lines in Figure 3d. The low S/N in this spectral range (S/N \( ^{\approx} 6 \)) yields a poor stringent upper limit on the S II column density and hence on the abundance of this element (see Tables 2 and 3).

3.7. System at \( z_{\text{abs}} = 2.4658 \) toward QSO 1223 + 178

In Figure 3e we show the S II portion of the spectrum already normalized to the broad absorption. The vertical dashed lines show the expected positions of the triplet. The S II \( \lambda 1259 \) line, if present, is heavily blended with a Ly\( \alpha \) interloper. The weakest \( \lambda 1250 \) absorption seems undetected in our S/N \( ^{\approx} 7 \) spectrum. If this is the case, we obtain \( \log N(S\ II) < 15.18 \) and an upper limit [S/Zn] \( ^{<} -0.01 \) by using the Zn II column density given by Pettini et al. (1994). However, the poor quality of the spectrum in the S II region and the difficulty in positioning the continuum precludes a reliable analysis of the S II triplet in this system, and for that reason we have omitted this DLA system from the rest of the present study.

4. DISCUSSION

4.1. Abundances of \( \alpha \)-Elements and Iron Peak Elements

In Table 3 we list the abundances of the iron peak elements Fe, Zn, and Cr, as well as the abundances of the \( \alpha \)-elements S and Si, for the DLA systems under investigation.
Iron peak elements are produced in nuclear statistical equilibrium and are expected to trace each other in the course of chemical evolution. Observations of metal-poor stars in the Galaxy confirm that Cr and Zn closely follow Fe in essentially solar proportions down to very low metallicities, although Cr deviates from this behavior, becoming slightly underabundant compared to iron at about [Fe/H] = −2 (Ryan et al. 1996; Sneden, Gratton, & Crocker 1991).

DLA systems which have metallicities [Zn/H] > −2 show instead systematic differences among the iron peak elements, with Zn more abundant than Cr and Fe. Abundances of these elements in the DLA systems under study are also given in Table 3. The systematic difference between Zn and Cr is attributed to differential depletion of these two elements from the gas phase to dust grains (Pettini et al. 1994, 1997). In fact, enhanced [Zn/Cr] and [Zn/Fe] ratios have been directly obtained from the saturated transition Fe II λ1608, and they warn that N(Fe II) must be underestimated; hence we use this value as a lower limit.

References—(1) Ge & Betchold 1997; (2) Pettini et al. 1994; (3) PW99; (4) this paper.

### Table 3

| QSO     | $z_{abs}$ | [S/Fe]$^a$ | [Si/Fe]$^a$ | [Fe/H]   | [Cr/H]   | [Zn/H]  | References$^b$ |
|---------|-----------|------------|-------------|----------|----------|---------|----------------|
| 0013−004 | 1.973     | −1.11 ± 0.14 | ...         | −1.84 ± 0.05 | ≤ −1.68 | −0.72 ± 0.13 | 1, 2, 2       |
| 0149+3335 | 2.141     | ≤ −0.97     | −1.68 ± 0.11 | −1.81 ± 0.10 | −1.37 ± 0.11 | −1.65 ± 0.14 | 3, 3, 3       |
| 0841+129  | 2.374     | −1.31 ± 0.23 | −1.27 ± 0.09 | −1.64 ± 0.17 | −1.56 ± 0.10 | −1.49 ± 0.10 | 4, 3, 3       |
| 0841+129  | 2.476     | −1.22 ± 0.23 | ≥ −1.85     | −1.84 ± 0.10 | −1.60 ± 0.11 | ≤ −1.63     | 3, 3, 3       |
| 1215+333   | 1.999     | < −1.37     | −1.47 ± 0.08 | ≥ −1.81$^d$ | −1.50 ± 0.08 | −1.31 ± 0.09 | 3, 3, 3       |
| 2231−0015  | 2.066     | ≥ −0.93     | −0.86 ± 0.10 | −1.32 ± 0.10 | −1.07 ± 0.11 | −0.75 ± 0.10 | 3, 3, 3       |

Note.—All abundances have been normalized to the meteorite values reported by Anders & Grevesse 1989: log (S/Fe)$_{0}$ = −4.73 ± 0.05, log (Si/Fe)$_{0}$ = −4.45 ± 0.02, log (Fe/Fe)$_{0}$ = −4.49 ± 0.01, log (Cr/Fe)$_{0}$ = −6.32 ± 0.03, log (Zn/Fe)$_{0}$ = −7.35 ± 0.02. Errors in [X/H] = log (X/H)$_{obs}$ − log (X/H)$_{0}$ include errors in X and H column densities and errors in solar abundances.

$^a$ From Si column densities obtained in this paper.

$^b$ From Si column densities given in PW99.

$^c$ References for the column densities of Fe II, Cr II, and Zn II, respectively.

$^d$ PW99 gave log N(Fe II) = 14.65 ± 0.04, derived from the saturated transition Fe II λ1608, and they warn that N(Fe II) must be underestimated; hence we use this value as a lower limit.

### Table 4

| [Zn/Fe]$_{corr}$ Abundance Ratios in DLA Systems |
|-------------------------------------------------|
| QSO     | $z_{abs}$ | [S/Zn] | [Si/Fe] | [Zn/Fe]$_{corr}$ |
|---------|-----------|--------|---------|-----------------|
| 0013−004 | 1.973     | −0.39 ± 0.14 | ... | ...             |
| 0100+1300 | 2.309     | −0.04 ± 0.08 | 0.37 ± 0.07 | 0.15            |
| 0347−3819$^b$ | 3.025 | ≥ −0.37 | 0.31 ± 0.03 | ...             |
| 0149+3335 | 2.141     | ≤ −0.68 | 0.13 ± 0.04 | 0.03            |
| 0526−2505$^b$ | 2.811 | −0.12 ± 0.09 | 0.51 ± 0.12 | 0.10            |
| 0841+129 | 2.374     | 0.18$^{+0.08}_{−0.21}$ | 0.37 ± 0.24 | 0.23            |
| 0841+129 | 2.476     | > 0.20$^a$ | > 0.01 | ...             |
| 1215+333 | 1.999     | < −0.46 | ≤ 0.34 ± 0.2 | 0.00            |
| 1331+170$^c$ | 1.776 | −0.11 ± 0.11 | 0.65 ± 0.10 | ...             |
| 2231−0015 | 2.066     | ≥ −0.18 | 0.46 ± 0.03 | 0.04            |
| 2348−147$^c$ | 2.279 | ≥ −0.89 | 0.37 ± 0.02 | ...             |

Note.—Relative abundances [X/Y] have been directly obtained from the column densities of X$^+$ and Y$^+$ species (references in Table 3, otherwise indicated) and using the meteorite values of Anders & Grevesse 1989. Errors in [X/Y] take into account error in [X$^+$] and [Y$^+$] column densities and errors in solar abundances. [Si/Fe]$_{corr}$ are ratios corrected by dust effects following Vladilo 1998.

$^a$ N(Fe II) from MCV98; N(Zn II) and N(Fe II) from PW99; N(Fe II) from Lu et al. 1998.

$^b$ N(Fe II) from Centurión et al. 1998; N(Zn II) from Pettini et al. 1994; N(Si II) and N(Fe II) from PW99.

$^c$ N(Si II), N(Si II), N(Zn II), and N(Fe II) from Lu et al. 1996.

$^d$ The most conservative value by using log N(S II) = 14.81−0.21; see Table 2.

$^e$ N(S II) from Kulkarni et al. 1996; N(Zn II), N(Si II), and N(Fe II) from PW99.

$^f$ N(S II), N(Si II), and N(Fe II) from Prochaka & Wolfe 1999; N(Zn II) from Pettini et al. 1994.
which molecular hydrogen has been detected (Ge & Betchold 1997). The presence of molecular gas is indicative of an environment hospitable to grains, and we should expect a large depletion of refractory elements. This is indeed confirmed by the much higher abundance of Zn compared to Fe (Table 3). In a dust-rich DLA system, Zn can be expected to be somewhat depleted—in a higher proportion than S as it occurs in the galactic ISM—and a slight enhancement of the [S/Zn] ratio could be expected. In order to quantify this effect we corrected the ratio [S/Zn]$_\text{corr}$ = −0.41 measured in this system following Vladilo (1998), and we obtained [S/Zn]$_\text{corr}$ = −0.41. The difference is very small and lower than the typical measurement errors, supporting the assumption that the S/Zn ratio is a reliable indicator of the $\alpha$/iron peak ratios in DLA systems also in the presence of a significant amount of dust.

Besides the problem of differential depletion, the ionization balance could also affect the measurement of the elemental abundance ratios as discussed recently by Howk & Savage (1999). From the presence of Al III at the same radial velocity of low ions in DLA systems, these authors argue that ionization effects can also produce an apparent velocity of low ions in DLA systems, these authors argue Savage (1999). From the presence of Al III at the same radial velocity of low ions in DLA systems, these authors argue that ionization effects can also produce an apparent velocity of low ions in DLA systems, these authors argue.
data is insufficient to firmly establish the presence of a correlation, which can be considered with the present data only if we use the [S/Zn] values in DLA systems at \( z_{\text{abs}} = 2.374 \) toward QSO 0841+129 as a measurement and not as an upper limit. In that case, a linear regression to the data yields a correlation coefficient of \( r = -0.77 \), obtained with only five data points (see Fig. 4). If confirmed by a larger data sample, the trend would be the first observational evidence of the expected decrease of the \( \alpha/\text{Fe} \) ratio in DLA systems during the course of chemical evolution. At variance with what is observed in our Galaxy, however, the \( \alpha/\text{iron peak} \) ratio attains solar values at low metallicity \( ([\text{Fe}/\text{H}] \approx -1) \) and decreases further at higher metallicities. This trend is the one predicted by chemical evolution models of galaxies with a low star formation rate (Matteucci, Molaro, & Vladilo 1997) and, if confirmed by future observations, it would have an important implication on the origin of DLA systems. Chemical evolutionary models predict \([\alpha/\text{Fe}] \approx 0\) at low metallicities \( ([\text{Fe}/\text{H}] \leq -1) \) when star formation proceeds in bursts separated by quiescent periods, as happens in dwarf galaxies, and when star formation is not as fast as in our Galaxy, as it happens in low surface brightness (LSB) galaxies and in the outer regions of disks (Jiménez, Bowen, & Matteucci 1999). In these galaxies, the metal enrichment is so slow that SNe Ia may have enough time to evolve and enrich the medium with iron peak elements in such a way as to balance the \( \alpha \)-elements previously produced by SNe II, when the overall metallicity is still low. In any case, by considering the sulphur abundance in DLA systems at \( z_{\text{abs}} = 2.374 \) toward QSO 0841+129 an upper limit, we may still conclude that the [S/Zn] ratios in DLA systems are markedly different from those observed in our Galaxy at comparable metallicities, implying a different chemical history.

In Figure 5 the [S/Zn] ratios are plotted versus the absorber redshift \( z_{\text{abs}} \). Chemical evolution effects should, in general, decrease the [S/Zn] with cosmic time, and one would expect a positive trend with \( z_{\text{abs}} \). Our sample, however, does not show such a correlation. Pettini et al. (1997, 1999) also do not find any trend of the [Zn/H] ratio with \( z_{\text{abs}} \), contrary to the expectation of a general increase of metallicity with cosmic time. A significant spread of [Zn/H] abundances at a given redshift is expected when different formation redshifts or spatial gradients are considered in modeling the intervening galaxies (Jiménez et al. 1998). Thus, different epochs of formation and different regions within a galaxy also could be responsible for the lack of correlation between [S/Zn] and redshift. The fact that we possibly detect a trend with [Zn/H] but not with \( z_{\text{abs}} \) suggests that metallicity is a better indicator of evolution since, contrary to redshift, it is independent of the epoch of formation of the individual galaxies. We do not exclude, however, that evolution with redshift can be detected when the data have a better redshift coverage.

It is worth mentioning that also in the Milky Way there are some measurements of \([\alpha/\text{Fe peak}]\) ratios not enhanced at low metallicity. These cases are found among halo dwarfs but are extremely rare. Carney et al. (1997) found \([\text{Mg/Fe}] = -0.31 \) in the star BD +80 245, while Nissen & Schuster (1997) found \([\text{Mg/Fe}]\) ratios ranging from \(-0.1\) to \( 0.2 \) in their stars. These stars are all characterized by large apogalactic distances, and the unusual abundance ratios have been interpreted as the chemical signature of a merger or accretion events. The stars before the merging or accretion process are thought to belong to a satellite galaxy that experienced a different chemical evolution history than the Milky Way. The presence of these cases do not imply, therefore, a connection between what we observe in DLA galaxies and the typical behavior of Milky Way chemical evolution.

We remark that also the nitrogen abundances in DLA systems do not seem to follow the behavior of Galactic metal-poor stars when dust-free \([\text{N/S}]\) or dust-corrected \([\text{N/Fe}_{\text{corr}}]\) ratios are used to determine the nitrogen relative abundances (Lu, Sargent, & Barlow 1998; Centurión et al. 1998).

We conclude that the DLA galaxies do not show the abundance properties usually expected for the progenitors of a spiral galaxy such as the Milky Way. The unusual abundance ratios suggest that the DLA galaxies are objects with low, or episodic, star formation rates such as LSB or dwarf galaxies. Part of the DLA systems may be protospirals, for which the line of sight samples the outer regions, which are known to have a slower evolution than the internal regions of disks.

These indications on the nature of DLA systems based on chemical abundances are in agreement with the results based on imaging studies at low redshifts, where the candidate DLA galaxies show a variety of morphological types, including dwarfs and LSB galaxies, while spirals are not the dominant contributors (Le Brun et al. 1997; Rao & Turnshek 1998). Nevertheless, it is important to remark that the spectroscopic sample of DLA systems is probably biased against detection of spirals since high column density clouds located in environments with relatively high metallicity and dust can be missed owing to obscuration of the background QSO (Pei, Fall, & Bechtold 1991; Vladilo 1999).
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