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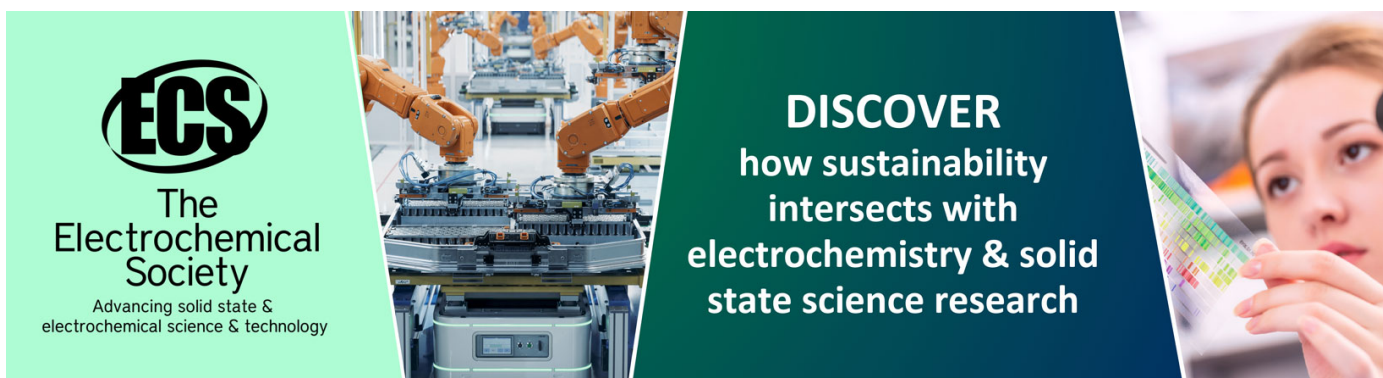
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Extremely strong damped Ly α systems at high redshifts

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Abstract. We present a spectroscopic analysis of seven Extremely Strong Damped Ly α systems at redshifts $z = 2-3$, obtained with the intermediate-resolution spectrograph X-shooter on the Very Large Telescope. For all systems we estimated column densities of the neutral atomic hydrogen H I, metal abundances and dust depletion. We firmly detected molecular hydrogen H₂ in two systems in our sample; for the remaining systems we set a conservative upper limits on the H₂ column densities. The properties of the obtained systems are in consistency with the sample of the Extremely Strong Damped Ly α systems available in the literature.

1. Introduction

The interstellar medium (ISM) is usually studied through the observation of emission lines. However, for remote galaxies such observations are averaged over the spatial resolution of the instruments, corresponding to the large volumes and/or wide surface areas of the gas, typically corresponding to a few kpc for high- z galaxies. Another independent method to study the ISM is to use absorption line analysis towards background sources. This method has many advantages over emission line studies: first, it provides column density measurements over very small scales (< 1 pc) corresponding to the size of emission regions of quasars used as a background sources. Secondly, high-resolution spectra enable the determination of column densities with very high precision and accuracy (< 0.1 dex). Thirdly, in contrast to emission line measurement, H₂ (the major constituent of molecular gas) is directly probed by absorption through resonant rest-frame UV lines, the so-called Lyman and Werner bands. Consequently, this technique allows one to probe the diffuse phases of the cold ISM [1] as well as “CO-dark” gas [2, 3] (which can be the dominant form of molecular gas at low metallicities), whereas these phases are hardly accessible through emission studies, even in our own galaxy.

Technically, such studies of remote galaxies are performed by analysis of Damped Ly α systems (DLAs), detected towards high-redshift quasars [4]. Besides the H I absorption lines, DLAs show a lot of associated absorption metal lines in various ionization states and, in some cases, molecular lines such as H₂ [5], HD [6] and CO [7]. It was shown that the DLA systems with the H I column density $\gtrsim 10^{21.7} \text{ cm}^{-2}$, so-called Extremely Strong Damped Ly α systems (ESDLAs), are associated with the galaxies at small impact parameters [8, 9], i.e. when the line of sight pass



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through the central part of the intervening galaxy. Therefore, an analysis of the ESDLAs allows one to directly probe the star-formation regions of high- z galaxies. In this paper we present an analysis of seven new ESDLAs at $z = 2 - 3$ and compare the properties of these systems with already known ESDLAs observed in the quasar spectra as well as DLAs in the γ -ray burst (GRB) afterglows, so-called GRB-DLAs.

2. Data

Observations of the seven quasars were carried out in service mode with the intermediate-resolution spectrograph X-shooter [10] on the Very Large Telescope under the program 0101.A-0891(A) in 2018 year. Observations were obtained with the nodding mode and $1''$, $0.9''$ and $0.9''$ slit widths for UVB, VIS and NIR arms, respectively. Characteristic seeing was $0.7 - 1.0$ arcsec. Data reduction was made using standard VLT Reflex pipeline. Wavelengths of each exposure were corrected for the heliocentric motion. Flux was corrected for the Galactic extinction by using the dust maps from [11]. The detailed description of the observations and data reduction will be present in Telikova et al. in prep.

3. Analysis

To analyse absorption features we use multicomponent Voigt-profile fitting procedure. The fitting results for all seven ESDLAs are summarised in table 1. Below we provide some details on the fit of certain species.

3.1. Neutral hydrogen

To estimate H I column density we fit Ly-series lines (in most cases $\text{Ly}\alpha$ and $\text{Ly}\beta$) using one-component Voigt-profile model. On the first step we estimated continuum by eye using B-spline interpolation. Since damped $\text{Ly}\alpha$ lines are wide and because the intrinsic (unabsorbed) quasar continuum is not known, for $\text{Ly}\alpha$ line we adjusted the continuum using Chebyshev polynomials¹, which was fitted simultaneously with H I lines. The b parameter was fixed during the H I fitting procedure, since $\text{Ly}\alpha$ and $\text{Ly}\beta$ absorption lines almost do not depend on it at high column density regime. Estimated H I column densities consistent with the values measured from the Sloan Digital Sky Survey spectra [9, 12].

3.2. Metallicity and dust depletion

Since we are interested in the neutral phase of ISM, we focus on the low-ionization metal species such as Si II, Zn II, Cr II, S II, Fe II, Mg II, Ni II, Ti II, Mn II, O I, C II. Metallicity and dust depletion were inferred relative to the solar abundances that were taken from [13]. To report the metallicity we used Zn since it is relatively confidently constrained and volatile element (i.e. is little depleted onto dust). For three ESDLAs we were able to estimate the column density of S II – another volatile element, and found that metallicities based on the Zn II and S II well agree with each other. For consistency here we provide the measurements based on Zn II for all systems. For each ESDLA we were able to estimate the Fe II depletion. Mean metallicity and Fe II depletion in our ESDLAs sample are $[\text{Zn}/\text{H}] = -1.3$ and $[\text{Fe}/\text{Zn}] = -0.5$ with standard deviations about 0.5 and 0.3, respectively. These values are in agreement with the other observations of the ESDLAs (e.g. [14]).

3.3. Molecular hydrogen

We searched for H_2 absorption lines using Lyman and Werner bands. We detected strong H_2 absorption with $\log N_{\text{H}_2} = 18.16 \pm 0.03$ and $\log N_{\text{H}_2} = 19.28 \pm 0.06$ in two systems toward J 2205+1021 and J 2359+1354, respectively. An example of the H_2 lines fit in ESDLA at

¹ The order of polynomial was defined based on the wavelength range and usually was 6 – 8.

$z = 3.255$ towards J 2205+1021 is shown in figure 1. For remained ESDLAs we estimated a conservative upper limits on H_2 column densities, using the similar method as in [14]. Briefly, we fixed Doppler parameter as $b = 1 \text{ km s}^{-1}$ and T_{01} temperature to be 100 K (which specify the relative population of $J = 0$ and $J = 1$ levels of H_2 that contain most H_2) and varied the total H_2 column density within the redshift range that corresponds to the measured velocity structure of the metal lines ($100 - 200 \text{ km s}^{-1}$, depending on the specific system). The upper limit of the N_{H_2} is expressed as the largest column density, which still does not contradict with the spectrum.

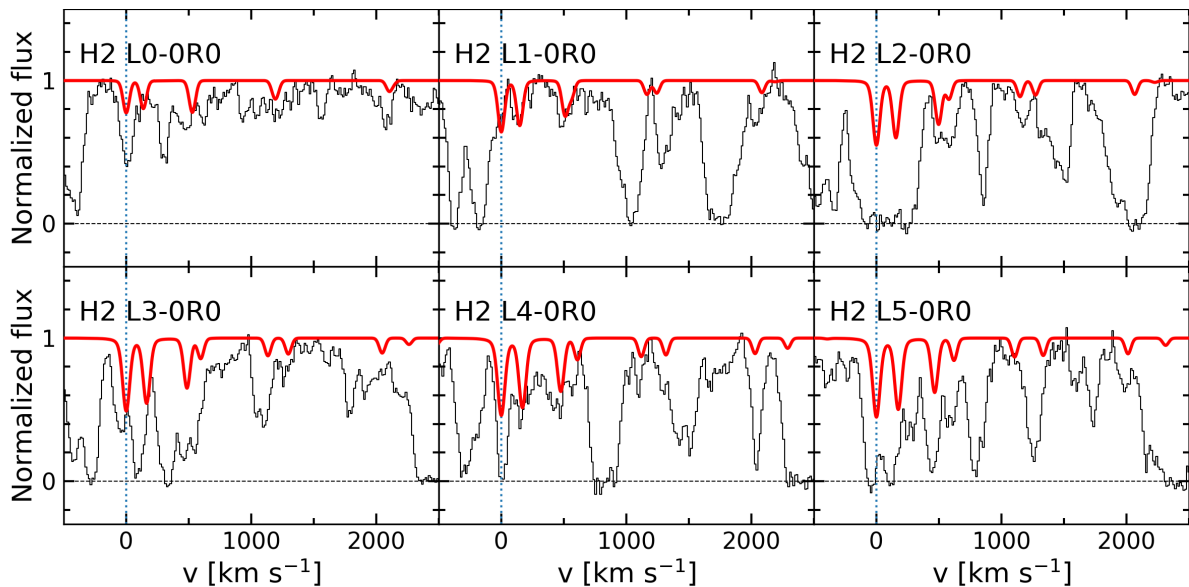


Figure 1. Fit to the H_2 absorption lines in ESDLA at $z = 3.255$ towards J 2205+1021. Voigt profiles are shown by red. Positions of the labeled transitions are indicated by the blue dashed lines.

3.4. Dust extinction

To calculate the dust reddening associated with ESDLAs we assumed the empirical extinction curve corresponded to the Small Magellanic Cloud [15]. As a template of unabsorbed quasar spectrum we used the composite spectrum from [16]. Statistical errors of the resulted reddening are negligible in comparison with systematic uncertainties, that arisen from unknown intrinsic shape of quasar spectrum. We found that system J 2359+1354 with the highest H_2 column density and the highest metallicity in our sample ($\log N_{H_2} = 19.28 \pm 0.06$ and $[Zn/H] = -0.47^{+0.03}_{-0.03}$, respectively) also demonstrates the highest dust extinction $A_V \approx 0.3$. Considering that Milky Way extinction-to-gas scaling relation [17] linearly scaled with metallicity we obtain higher $A_V \sim 1.4$ than measured in J 2359+1354.

4. Discussion

Our sample enlarges the sample of ESDLAs at high redshifts detected towards QSO sightlines and analysed in high-resolution spectra [14]. Therefore it is reasonable to look how the properties of analysed ESDLAs represent the previous sample. Additionally, it was found that DLAs detected in GRB afterglows have similar properties with ESDLA sample [14, 18]. Therefore we compare our sample with them both. In figure 2 we show the metallicity-depletion

Table 1. Fitting results.

Quasar	z_{abs}	$\log N_{\text{HI}}$	$\log N_{\text{H}_2}$	$[\text{Zn}/\text{H}]$	$[\text{Fe}/\text{Zn}]$	$A_V^\dagger$
J 0024−0725	2.68120	$21.81^{+0.01}_{-0.01}$	< 17.20	$-1.77^{+0.06}_{-0.09}$	$-0.56^{+0.10}_{-0.09}$	0.03
J 1238+1620	3.20907	$21.60^{+0.01}_{-0.01}$	< 17.25	$-1.01^{+0.05}_{-0.05}$	$-0.43^{+0.06}_{-0.05}$	−0.02
J 1353+0956	3.33326	$21.61^{+0.01}_{-0.01}$	< 17.30	$-1.64^{+0.22}_{-0.28}$	$-0.43^{+0.36}_{-0.32}$	0.05
J 1418+0718	2.39211	$21.59^{+0.02}_{-0.02}$	< 17.20	$-1.88^{+0.32}_{-1.05}$	$0.01^{+1.04}_{-0.33}$	0.01
J 2205+1021	3.25516	$21.61^{+0.02}_{-0.02}$	18.16 ± 0.03	$-0.93^{+0.05}_{-0.05}$	$-0.87^{+0.09}_{-0.07}$	0.09
J 2351−0639	2.55744	$21.90^{+0.01}_{-0.01}$	< 17.75	$-1.58^{+0.05}_{-0.05}$	$-0.46^{+0.11}_{-0.11}$	0.03
J 2359+1354	2.2499	$21.96^{+0.02}_{-0.02}$	19.28 ± 0.06	$-0.47^{+0.03}_{-0.03}$	$-0.94^{+0.03}_{-0.03}$	0.29

[†] The uncertainty of A_V is ~ 0.1 and dominated by the systematic uncertainty concerned with the dispersion of intrinsic shapes of quasar spectra (see e.g. [14]).

diagram for these samples. One can see that, while our sample located at the same region in metallicities-depletion plane as the literature samples, it has three (out of seven) ESDLAs with metallicity $\gtrsim -1$. This fraction is higher in comparison with both literature samples.

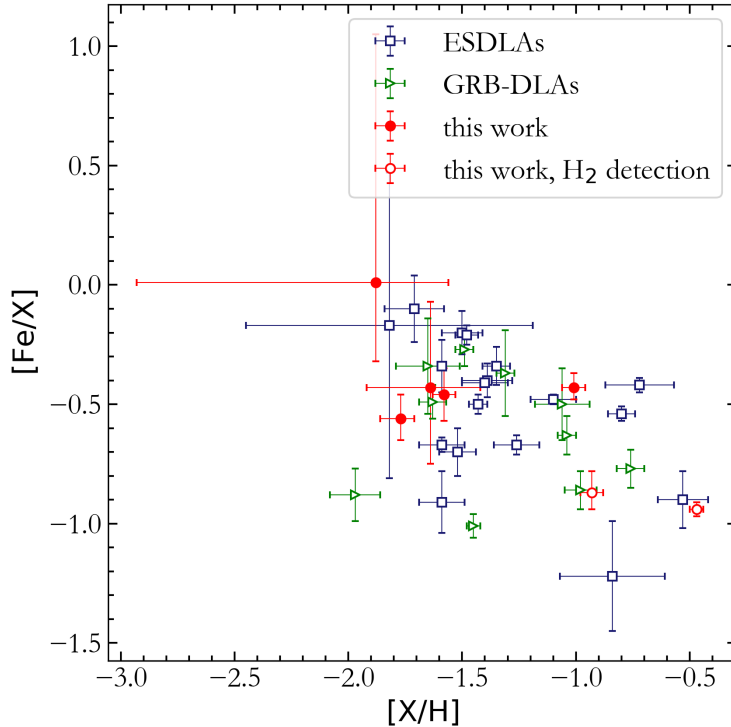


Figure 2. Fe II depletion vs. metallicity. ESDLA systems from [3, 14, 20, 21] are shown by the blue open squares. Green triangles correspond to the GRB-DLA systems from [18]. Our results are shown by the red circles. Red open circles correspond to the systems with H₂ detection. X is the volatile species (Zn or S). Choice of the volatile species depends on the properties of the exact system.

In two systems we detected H₂ absorption, which is in a agreement with the 30 – 50 per cents of the incidence rate of strong H₂ absorption ($\log N_{\text{H}_2} \gtrsim 18$) in ESDLAs, obtained in the previous studies [14, 19]. Additionally, for the ESDLA with the highest H₂ column density on our sample, J 2359+1353, we found the presence of the neutral carbon C I, which is known as a good tracer of the molecular hydrogen [22] and cold gas. This system also demonstrates the highest H I column density $\log N_{\text{HI}} = 21.96$ and metallicity $[\text{Zn}/\text{H}] = -0.47$. For the remained five systems the upper limits on H₂ did not stem out in comparison with literature samples. Indeed, in figure 3

we compare the H_2/HI abundances in absorption systems at high redshifts. Besides the ESDLA samples we plot the H_2/HI data for regular DLAs at high redshifts (see references in [2]). One can see that estimated upper limits on $\log N_{\text{H}_2}$ in our seven ESDLA systems do not contradict with the H_2 incidence rate based on the total ESDLA sample. The derived loose upper limits on H_2 column density are in most cases due to spectral quality and significant contamination of $\text{Ly}\alpha$ forest lines. Therefore, the high-resolution spectra are essentially needed for this sample, especially, since such systems at high HI regime provide a way to constraint HI– H_2 transition in ISM at low metallicities.

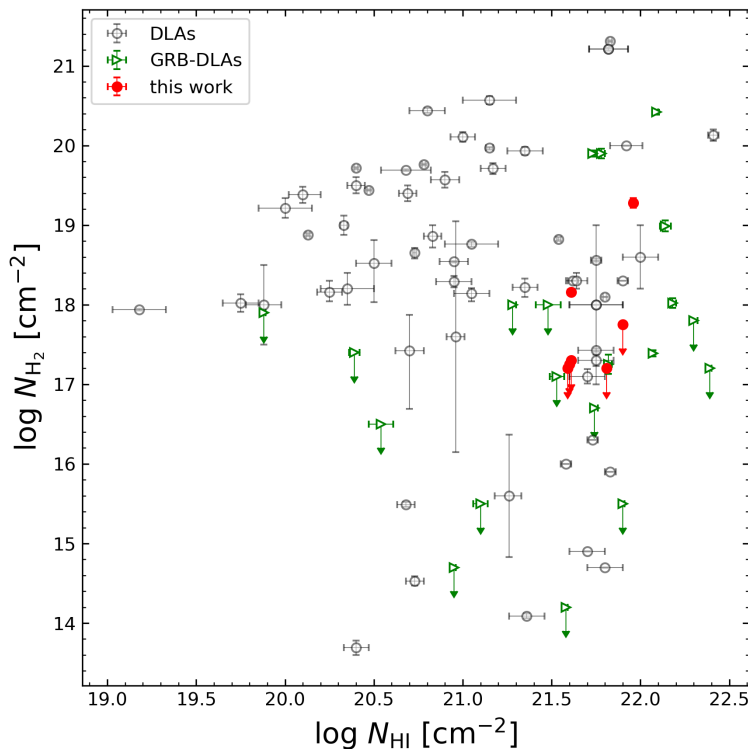


Figure 3. Column densities of HI vs. H_2 . DLA systems are shown by the grey open circles [1, and references therein]. Green triangles correspond to the GRB-DLA systems from [18]. Our results are shown by the red filled circles.

One of the most important property of ESDLA systems is the very small impact parameters measured in case of detection of associated emission lines [14]. Therefore, we also inspected 2D spectra of analysed ESDLAs for the presence of main emission lines $\text{O II } \lambda\lambda 3727, 3729\text{\AA}$, $\text{O III } \lambda\lambda 4959, 5007\text{\AA}$ and $\text{H}\alpha$. These emission lines are usually used to estimate the star-formation rates ESDLAs counterparts. Unfortunately, for all obtained spectra we found no detection of the emission lines.

In three ESDLAs, namely, J0024–0725, J1353+0956 and J1418+0718, we measured the column density of C II^* using $\text{C II}^* \lambda 1335\text{\AA}$ line. As it was proposed in [23], C II^* absorption can be used for estimation of the star-formation rate via calculating the cooling rate corresponded to the $\text{C II } \lambda 158\mu\text{m}$ emission and ESDLA systems assumed to probe the central star-forming part of DLAs. We found the cooling rates to be $\log l_c \approx -27.7, -27.4$ and -27.5 [$\text{erg s}^{-1} \text{H}^{-1}$] in J0024–0725, J1353+0956 and J1418+0718, respectively. These values agree with earlier measurements of the cooling rates for DLAs [24], but our sample probes the higher N_{HI} range than previous measurements. However, we should note that in present spectra, we can not reject the strong saturation in observed $\text{C II}^* \lambda 1335\text{\AA}$ absorption, that can lead to the ambiguous results. Therefore, here we suppose that determination the star-formation rates from these values can be too optimistic.

5. Conclusions

Using the Voigt-profile fitting we analysed seven new ESDLA systems with H I column densities $\log N_{\text{HI}} > 21.6$ at $z = 2 - 3$ in the quasar spectra, obtained with the intermediate-resolution spectrograph X-shooter on the Very Large Telescope. In all systems we estimated H I column densities, metal abundances and dust depletion. Mean values zinc-to-hydrogen and iron-to-zinc ratios of the systems are $[\text{Zn}/\text{H}] = -1.3$ and $[\text{Fe}/\text{Zn}] = -0.5$ with standard deviations about 0.5 and 0.3, respectively. We detected strong H₂ absorptions in two ESDLAs in our sample; for other five systems we set a conservative upper limits on the total H₂ column densities. We summarise that obtained gas properties such as metallicity, dust depletion and H₂ content are in agreement with that of the total DLA sample both for systems, which were detected in the quasar spectra and GRB afterglows.

Acknowledgments

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