

Optical-NIR spectra of quasars close to reionization ($z \sim 6$)^{*}

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X-shooter, with its characteristics of resolution, spectral coverage and efficiency, provides a unique opportunity to obtain spectra of the highest-redshift quasars ($z \sim 6$) that will allow us to carry out successful investigations on key cosmological issues, from the details of the re-ionization process, to the evolution of the first galaxies and AGNs. In this paper, we present the spectra of three $z \sim 6$ quasars: one obtained during the commissioning of X-shooter and two in the context of our ongoing GTO programme. Combining this sample with data in the literature, we update the value of the C IV cosmic mass density in the range $4.5 \leq z \leq 5$, confirming the constant trend with redshift between 2.5 and 5.

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1 Introduction

The properties of stars, galaxies and quasars in the local and early Universe can be investigated through their impact on the intergalactic medium (IGM). In particular, the radiation emitted and the metals ejected from these objects re-ionized and polluted the IGM. As a consequence, the detailed understanding of these mechanisms has the potential to significantly constrain models for the formation and evolution of galaxies and quasars, and the re-ionization history of the Universe. The IGM is mainly studied through the absorption signature it leaves in bright high-redshift sources, quasars and Gamma-Ray Bursts (GRBs). The highest redshift quasars have been detected mainly by the Sloan Survey (SDSS) at $z \sim 6$ (e.g. Fan et al. 2001), corresponding to ~ 1 billion years after the Big Bang. This sample of ~ 20 objects has been used to investigate several topics, in particular the ionization and chemical status of the IGM at these high redshifts.

The fact that the spectra of the high- z quasars show some extended regions of zero transmission in the Ly α forest (e.g. Becker et al. 2001) was interpreted as the signature of relatively large H I densities at those redshifts (the so called “Gunn-Peterson effect”, Gunn & Peterson 1965).

However, due to the high sensitivity of the Gunn-Peterson (GP) optical depth, τ_{GP} , to tiny neutral hydrogen fractions ($x_{\text{HI}} > 10^{-3}$ – 10^{-4}), the detection of a GP trough only translates into a lower limit for the volume averaged neutral hydrogen fraction. Nevertheless, the sudden rise of the Ly α opacity approaching $z \sim 6$, was considered as an evidence for the reionization of the Universe to be completed by this epoch (e.g., Fan et al. 2006, but see also Becker et al. 2007). More sophisticated approaches to the investigation of the reionization epoch with the Ly α forest are represented by the statistics of the dark gaps (e.g., Fan et al. 2006; Gallerani et al. 2006, 2008) and the application of the *apparent shrinking criterion* (Maselli et al. 2007, 2009) which compares the observed size of the flux transmission window around the quasar with the size of the quasar H II region predicted by radiative transfer simulations. Both methods applied to the sample of spectra available from the literature suggest that the IGM at $z \sim 6$ is already highly ionized. However, systematic errors (due, e.g., to the uncertainty in the systemic redshift of the quasar or in the position of the level of the continuum) still play an important role and undermine the reliability of the obtained results.

The same high- z quasars can be used to put an indirect constraint on the epoch of re-ionization by investigating the redshift evolution of metal abundances traced by ionic absorption lines. Indeed, the main sources of ionizing photons are now thought to be massive stars, which are also the bulk producers of heavy elements. The investigation of

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the regime beyond $z \sim 5$ is essential since in this redshift range the comoving star formation rate density appears to decline (e.g. Mannucci et al. 2007; Gonzalez et al 2010). If a similar behaviour is observed for the mass density of metals in the IGM, then a scenario where winds from massive star-forming galaxies pollute the IGM with metals would be favoured. On the other hand, if the mass density of metals is observed to remain constant, this would point to an epoch of very early enrichment of the IGM, presumably by smaller mass objects (e.g. Pop. III stars), when shallow potential wells allow winds to distribute metals over large comoving volumes, thus producing a quite uniform metallicity distribution (e.g. Madau et al. 2001). The most recent compilation of the evolution with redshift of the C IV cosmic mass density (D'Odorico et al. 2010) shows a flat behaviour in the range $z \simeq 3$ –5 and a possible downturn at $z > 5$. The latter result needs confirmation since the point at $z \simeq 5.5$ is based on just four C IV absorptions (Ryan-Weber et al. 2009). The more conservative result by Becker et al. (2009) is consistent with an invariant value up to $z \sim 6$. Intergalactic absorption-line detections at these redshifts are rare because the C IV doublet moves into the near-infrared spectral region. Absorption line spectroscopy is much more challenging in this regime because of increased detector noise, OH emission from the sky and more severe telluric absorption.

As soon as metals start to be produced and ejected in the diffuse medium, part of them condenses into microscopic solid particles, giving birth to the interstellar dust of the first galaxies. Characterizing the properties of this dust at high- z is important to improve our understanding of the early cosmic epochs. High redshift quasars contain large dust masses, which have been revealed by mm and sub-mm observations. Yet, the origin of dust at such early epochs is still unclear. Among the stellar sources, the cool and dense atmosphere of asymptotic giant branch (AGB) stars and the expanding ejecta of core collapse supernovae (SN) offer the most viable sites of dust grains condensation. However, AGB stars require about 1 Gyr to evolve in large number, and therefore to effectively enrich the interstellar medium with dust (but see Valiante et al. 2009). This timescale is comparable to the age of the Universe at redshift $z \sim 6$.

On the other hand, since dust pollution by SNe can occur on shorter timescales ($\sim 10^6$ yr), a SN origin has often been advocated as the only possible explanation for the large amount of dust observed in high redshift quasars. This scenario has been tested through observations of the reddened quasar SDSS J1048+4637 at $z_{\text{em}} = 6.2$ (Maiolino et al. 2004), the $z_{\text{em}} = 6.29$ GRB 050904 (Stratta et al. 2007) and the $z_{\text{em}} \simeq 5$ GRB,071025 (Perley et al. 2010). In these sources, the inferred dust extinction curve is different with respect to any of the extinction curves observed at low z , and it shows a very good agreement with the extinction curve predicted for dust formed in SN ejecta. This is an indication that the properties of dust may evolve be-

Table 1 Journal of observations. All spectra were obtained using the combination of slits 1.0/0.9/0.9 arcsec in the UVB/VIS/NIR arms, respectively.

QSO	z_{em}	J (mag)	Date (UT)	Exp. (s)
J1306+0356 ¹	6.016	18.77	2009 Mar 19	5 400
J0818+1722 ³	6.00	18.54	2010 Jan 21	19 600
			2010 Jan 22	3 310
J1509–1749 ²	6.12	18.78	2010 May 18	18 000
			2010 May 19	6 000

¹ Fan et al. (2001); ² Willott et al. (2007); ³ Fan et al. (2006).

yond $z > 5$ –6. Recently, Gallerani et al. (2010) have analyzed the dust properties of a sample of 33 quasars with $4 < z_{\text{em}} < 6.4$. The 7 quasars in the sample showing significant reddening are well described by SN-type extinction curves. Marginal evidence of reddening is detected in almost all the quasars of the sample, however a conclusive result cannot be reached due to the limited resolution ($R < 800$) and wavelength coverage of the available spectra.

The X-shooter spectrograph, with its high sensitivity, extended spectral coverage and intermediate resolution (see contributions by S. D'Odorico, J. Vernet, and F. Zerbi), appears to be the ideal instrument to obtain data of the needed quality to allow significant steps forward in the above fields of research. For this reason, we have proposed a programme (PI. V. D'Odorico) to observe the brightest ($J_{\text{Vega}} \lesssim 19$) quasars known with $z_{\text{em}} \gtrsim 5.7$ observable from Paranal, in the Italian guaranteed time of observation (GTO). 7 objects satisfy our selection criteria. In the meantime, two of them (SDSS J1306+0356 and ULAS J1319+0950) have been extensively observed by a competing programme carried out in open time.

In the following, we describe the present status of our programme.

2 Data observation, reduction, and analysis

The total time assigned to our GTO programme was of ~ 6 nights (52 hours) and observations started in January 2010. GTO is carried out in visitor mode. Due to bad weather and technical problems, we have lost more than half of the assigned nighttime, up to now. At present, we have obtained the spectra of two quasars: J0818+1722 and J1509–1749 which are described below, together with the spectrum of J1306+0356 observed during the third commissioning run. The details of the observations are reported in Table 1. In the 2.5 nights still available to complete the programme, we plan to observe three more objects.

All the raw frames were reduced with the public release of the X-shooter pipeline (see contributions by P. Goldoni and by A. Modigliani). We followed the standard steps of the reduction, except for the extraction of the 1D spectra from the 2D merged spectra for which we used the command ‘extract/long’ in MIDAS (using a predefined aperture)

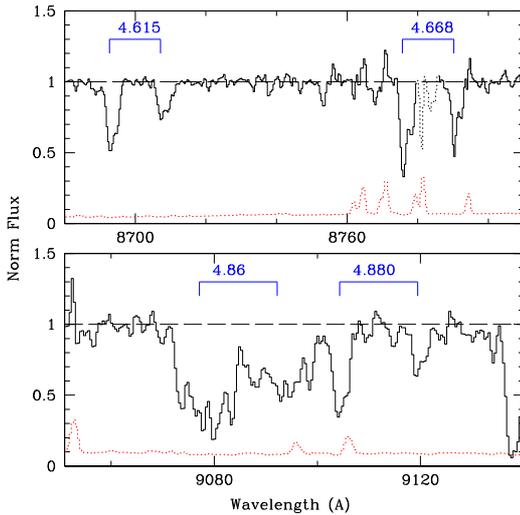


Fig. 1 (online colour at: www.an-journal.org) C IV absorptions detected in the spectrum of J1306+0356. The doublets are marked together with their absorption redshift.

which gives better results than the pipeline, at least for such faint objects. The instrument response curve was obtained reducing with the specific pipeline recipe the standard flux stars observed the same night of the scientific observations. Each extracted frame was then flux calibrated by dividing for the response curve. Finally, the set of 1D spectra obtained for each object was added with a weighted sum to obtain the final spectrum.

The continuum level in the region redward of the Ly α emission was determined interpolating with a spline polynomial of 3rd degree the portions of the spectrum free from absorption lines. The same approach cannot be applied to the heavily absorbed Ly α forest. The continuum in this spectral range was obtained by extrapolating the power law which fits the red region cleaned from the intrinsic emission lines.

Finally, the VIS and NIR spectra were corrected for telluric absorption dividing by the normalized spectrum of standard spectroscopic stars observed with the same instrumental set-up as the QSOs in our sample, using the command ‘telluric’ in IRAF.

In the following, all the reported signal to noise ratios (SNR) are per wavelength bin: 0.4 Å in the VIS arm and 0.6 Å in the NIR arm.

2.1 SDSS J1306+0356

This object was studied in the past at low/intermediate resolution in particular with GNIRS at Gemini South Observatory and with ISAAC at the VLT. The spectrum analysed here was obtained during the 3rd commissioning of X-shooter and has a relatively low SNR with respect to the other two spectra: $\simeq 30$ on the Ly α emission, decreasing to 8–10 down to 1 μm .

Jiang et al. (2007) detected 4 Mg II systems at $z_{\text{abs}} = 2.20, 2.53, 4.86,$ and 4.88 (see also Kurk et al. 2007). We

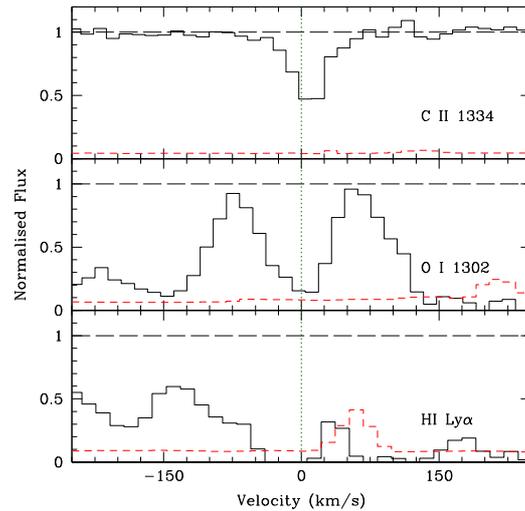


Fig. 2 (online colour at: www.an-journal.org) Possible absorption system at $z_{\text{abs}} = 5.4347$ in the spectrum at J1306+0356. The O I line falls in the Ly α forest.

confirm the presence of the three higher-redshift Mg II systems. On the other hand, we identify the two lines previously interpreted as the Mg II doublet at $z_{\text{abs}} = 2.20$ as the Si II 1526 Å absorptions at $z_{\text{abs}} = 4.86$ and 4.88 , respectively. For these two systems we detect also the C IV transitions (see Fig. 1). The line identified as Mg I 2852 for the system at $z_{\text{abs}} = 2.20$ is instead Fe II 2586 at $z_{\text{abs}} = 2.53$.

We detect two more C IV systems at $z_{\text{abs}} = 4.615$ (with associated Si II 1526 and Al II 1670) and 4.668 , a possible weak Mg II doublet at $z_{\text{abs}} = 2.309$ and a possible system at $z_{\text{abs}} = 5.435$ with O I 1302, and C II 1334 Å (see Fig. 2).

Previous observations did not identify reliable C IV absorptions in the Z, J bands (corresponding to $z_{\text{abs}} \simeq 5-6$, see Ryan-Weber et al. 2006; Simcoe 2006), and unfortunately the NIR portion of the X-shooter spectrum of J1306+0356 has a SNR too low to be used.

2.2 SDSS J0818+1722

The spectrum of J0818+1722 is the best of our present sample, with a SNR varying between ~ 80 and 20 in the VIS region (redward of the Ly α emission) and 17 and 45 in the C IV forest extending into the NIR region. Thanks to the high SNR, we could subtract quite well the telluric features, in particular in the VIS region, revealing the presence of many absorption systems. In particular, we detected C IV doublets at $z_{\text{abs}} = 4.463, 4.498, 4.508, 4.523, 4.552, 4.577, 4.620, 4.727$ (complex), $4.732, 4.877, 4.942, 5.076, 5.308, 5.322, 5.324$; two possible, very weak Mg II doublets at $z_{\text{abs}} = 2.0906$ and 2.129 and one very well defined with associated Fe II lines at $z_{\text{abs}} = 3.5628$ (in the NIR portion of the spectrum).

Previous spectroscopic studies of this SDSS QSO have been carried out with NIRSPEC at the Keck telescope (Becker et al. 2009) and with ISAAC at the VLT (Ryan-Weber et al. 2009). The latter spectrum shows a tenta-

Table 2 Ω_{CIV} for the systems in the total sample selected in the reported column density intervals.

$\log N(\text{CIV})$	$\langle z \rangle$	ΔX	lines ($\times 10^{-8}$)	Ω_{CIV} ($\times 10^{-8}$)	$\delta\Omega$
13.0–15.0	4.7	10.08	32	2.6	0.6
13.8–15.0	4.8	10.08	10	1.7	0.6

tive C IV doublet at $z_{\text{abs}} = 5.7899$ and an Mg II doublet at $z_{\text{abs}} = 2.8341$. The presence of the Mg II system is not confirmed by our spectrum, we could not find any line at this redshift, neither the Mg II doublet nor the strong transitions due to Fe II 2382 and 2600 Å, that would have fallen in the high SNR VIS region. On the other hand, also our data show a tentative C IV doublet at $z_{\text{abs}} \simeq 5.79$. Furthermore, we detected several strong low ionization lines at this redshift with a velocity profile fitted by three main components: Si II 1260, O I 1302, C II 1334, Fe II 2344, 2382. Another metal system showing the same ionic transitions has been detected at $z_{\text{abs}} \simeq 5.876$. A further paper will be devoted to the detailed analysis of these metal absorption systems (D'Odorico et al., in preparation).

2.3 CFHQS J1509–1749

This object was discovered relatively recently (Willott et al. 2007) and it is the least studied of our small sample. Our spectrum is, to our knowledge, the first to be reported in the literature at intermediate resolution. The SNR in the VIS region (redward of the Ly α emission) varies between 40 and 15. In the NIR region, in particular in the C IV forest, SNR ~ 10 –20.

In the discovery paper, Willott and collaborators reported the detection of two Mg II doublets at $z_{\text{abs}} = 3.266$ and 3.392 (the latter with associated Mg I 2852 and Fe II 2344, 2382, 2586, 2600 Å transitions). We confirm the presence of these two systems and add more transitions to them (in particular Zn II at $z_{\text{abs}} = 3.392$). Furthermore, we identify a new Mg II doublet at $z_{\text{abs}} = 3.128$ with associated Fe II lines. In the VIS portion of the spectrum, we identify 5 C IV doublets at $z_{\text{abs}} = 4.611, 4.642, 4.666, 4.792,$ and 4.816, while no C IV is detected at $z > 5$ in the NIR spectrum.

3 The CIV mass density at $z \simeq 4.5$ –5

The C IV mass density, Ω_{CIV} , is a measure of the amount of metals present in the IGM at a given redshift (see, e.g., D'Odorico et al. 2010 for the details of the computation).

The value of Ω_{CIV} in the redshift range $4.5 \lesssim z \lesssim 5.0$ was computed by Pettini et al. (2003) with the spectra of three high- z quasars obtained with ESI at the Keck telescope. By adding the present sample to that of Pettini and collaborators, we increase by a factor ~ 3 both the spanned redshift absorption path (from 3.5 to 10) and the number

of detected lines¹ (from 11 to 32). The computed Ω_{CIV} for two ranges of C IV column densities are reported in Table 2. They are in very good agreement with the original result by Pettini et al. (2003) corrected to the Λ CDM concordance cosmology and with the re-computation by Ryan-Weber et al. (2009) to the column density range $13.8 \leq \log N_{\text{CIV}} \leq 15$.

This result put on a firmer ground the observed constant behaviour of Ω_{CIV} in the redshift range $2.5 < z < 5$. More spectra are needed to compute a reliable value of Ω_{CIV} beyond $z \sim 5$: this is one of the final goals of our GTO programme.

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¹ In the column density range $13 \leq \log N_{\text{CIV}} \leq 15$