Tracking the chemical history of the Universe: the density of C IV at $z \sim 6$

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Resumen / Espectroscopía de cuasares (QSO, por sus siglas en inglés) a alto corrimiento al rojo (z) ha revelado la existencia de líneas de absorción producidas por metales en la línea de la visual al QSO. La evidencia de carbono puede seguirse hasta tiempos cósmicos muy tempranos, y demuestra que ya existían metales en el medio intergaláctico tan sólo ~ 1 Ga después de la gran explosión. En este trabajo, buscamos sistemas de absorpción con C IV a $z > 5$ en siete líneas de la visual a QSO que no han sido incluidas en otros estudios. Determinamos la densidad comóvil de masa de C IV ($\Omega_{\rm C\,IV}$), la cual es una medida integral de la masa en metales y los fotones ionizantes emitidos por generaciones de estrellas anteriores, y hallamos que nuestro resultado es consistente con la existencia de un rápido descenso en el C IV intergaláctico a $z > 5$.

Abstract / Spectroscopy of high redshift (z) quasars (QSOs) has revealed the existence of absorption lines produced by metals in the line of sight to the QSO. The signature of carbon can be followed to very early cosmic times, showing that metals already exist in the intergalactic medium only ~ 1 Gyr after the Big Bang. In this work, we search for C IV absorption systems at $z > 5$ in seven QSO lines-of-sight not included in other studies. We determine the C IV comoving mass density ($\Omega_{\rm C\,IV}$), which is an integral measure of the amount of metals and ionizing photons emitted by previous generations of stars, and find that our current result is consistent with a rapid drop of intergalactic C IV at $z > 5$.

Keywords / intergalactic medium — quasars: absorption lines — techniques: spectroscopic

1. Introduction

The formation and evolution of galaxies at high redshift involves inflowing gas to fuel star formation (e.g. Crighton et al., 2015) and feedback from exploding supernovae to push the gas out of the galaxies at velocities of hundreds of km s^{-1} (e.g. Martin et al., 2012; Karman et al., 2014). These outflows are able to chemically enrich the circum and intergalactic medium (CGM & IGM). This picture is supported by metal line systems observed in absorption in the spectra of high redshift quasars (QSOs) (e.g. Adelberger et al., 2005; Kacprzak et al., 2014; Crighton et al., 2015). They are windows to diffuse gas in and around galaxies, which we use to test the connection between galaxies and the IGM to reconstruct the history of baryons.

Metal absorption systems are useful tracers of metallicity and ionization state of regions of the Universe that cannot be observed in emission. For example, the absorption line doublet of triply ionized carbon (C IV) is sensitive to chemically enriched and highly ionized gas (Oppenheimer et al., 2009; Tescari et al., 2011; Pallottini et al., 2014). This transition is commonly observed and used as tracer of metals across cosmic time. Moreover, it is particularly important during the epoch of reionization of intergalactic hydrogen at redshift $z \geq 6$ (Becker et al., 2015) because it can arise from galaxies that are fainter than the detection limits of current galaxy surveys.

In two pilot studies, Simcoe (2006) and Ryan-Weber et al. (2006) made the first measurements of C IV in the spectra of $z \sim 6$ QSOs. Up to now, only 13 lines of sight have been used on surveys of C IV at $z > 5$ (Becker et al., 2009; Ryan-Weber et al., 2009; Simcoe et al., 2011; D'Odorico et al., 2013). This work is an update to our survey of C IV systems at $z > 5$ (Ryan-Weber et al., 2006, 2009). It includes seven NIRSPEC spectra of $z_{\rm em} > 5.7$ QSOs that have not been surveyed for C IV before. This paper is organised as follows. Sec. 2 describes the data and measurement of C IV systems. The value of $\Omega_{\rm C\,IV}$ at $z > 5.1$ is determined in Sec. 3. Finally, the result is discussed in Sec. 4. We assume a flat Universe with $H_0 = 70$ km s^{-1} Mpc^{-1} ($h_{100} = 0.7$), $\Omega_{\rm M} = 0.3$ and $\Omega_\Lambda = 0.7$, where H_0 is the Hubble constant, h_{100} the Hubble parameter, $\Omega_{\rm M}$ the matter density and Ω_Λ the vacuum density, today.

2. Observation and detection of C IV systems

Eight QSOs with emission redshift $z_{\rm em} > 5.7$ were observed with the Keck II telescope using the cross-

Table 1: Lines of sight observed with NIRSPEC. Columns are: (1) reference number of the QSO from Sloan Digital Sky Survey (SDSS), (2) emission redshift, (3) range of signal-to-noise ratio, (4) redshift range, and (5) surveyed absorption path length.

QSO	$z_{\rm em}$	S/N	$z_{\rm min}$–$z_{\rm max}$	ΔX
J0005−0006	5.850	10–15	5.156–5.736	2.65
J0303−0019	6.070	~ 10	5.330–5.808	2.20
J0818+1722	6.002	40–60	5.136–5.885	3.43
J0841+2905	5.96	20–40	5.136–5.844	3.23
J0842+1218	6.055	10–15	5.201–5.937	3.39
J0927+2001	5.79	10–20	5.156–5.677	2.37
J1207+0630	6.040	10–15	5.252–5.923	3.09
J1335+3533	5.93	20–30	5.143–5.814	3.06
J0840+5624[a]	5.774	10–22	5.159–5.661	2.28
J1137+3549[a]	5.962	20–40	5.136–5.846	3.24
J1148+5251[a]	6.421	16–30	5.136–6.247	5.15
J1602+4228[a]	6.051	17–48	5.143–5.933	3.63
J2054−0005[a]	6.062	8–12	5.330–5.944	2.84

[a]From Ryan-Weber et al. (2009).

dispersed near-infrared echelle spectrograph NIRSPEC (McLean et al., 1998), between the years 2008 and 2009. We used the low-resolution ($R \sim 1500$) setting NIRSPEC-1 and a 0.57" slit, resulting in a spectral resolution of FWHM=6.4 Å (185 km s^{-1} at 10 335 Å), which is sampled with 2.1 pixels. The wavelength range is between 9450 Å and 11 210 Å. Data were reduced as described in Ryan-Weber et al. (2009). More details of the sample are presented in Table 1.

Each spectrum was normalized and visually inspected. Using the PYTHON routines PLOTVEL and PLOTSPEC*, we searched for any pair of absorption lines with an observed wavelength matching the two components of a redshifted C IV doublet ($\lambda_0 = 1548.2049, 1550.7784$ Å). A C IV system candidate is identified if the λ1548 Å component is detected at more than 3σ (i.e. $\mathrm{W_0}(1548)/\sigma_{\mathrm{W0}}(1548) > 3$). Finally, we removed fake systems resulting from the subtraction of sky emission lines and we only consider the candidates at more than 5000 km s^{-1} in radial velocity from the QSO. The C IV doublets were further analysed with VPFIT** to determine the redshift (z), the logarithm of the column density ($\log(N(\mathrm{C\,IV}))$) and the Doppler parameter (b) of the absorbing gas from a Voigt profile fitting. Several fits were attempted to ensure consistency (convergence) on the parameters obtained with VPFIT. More details on individual systems will be included in a forthcoming publication.

3. The comoving mass density of C IV at $z > 5.1$

We calculate the comoving mass density of C IV $\Omega_{\rm C\,IV}$, expressed as a fraction of the critical density today, from the integral of the column density distribution function $f(N(\mathrm{C\,IV}))$, which is the number of absorption lines per unit of column density ($N(\mathrm{C\,IV})$) and per unit of redshift absorption path dX. However, the sample of absorption systems is too small to recover a reliable $f(N(\mathrm{C\,IV}))$. The solution is to approximate the integral by a sum which results in

$$\Omega_{\rm C\,IV} = \frac{H_0\, m_{\rm C\,IV}}{c\,\rho_{\rm crit}} \frac{\sum_i N_i(\mathrm{C\,IV})}{\Delta X}, \qquad (1)$$

where $m_{\rm CIV}$ is the mass of a C IV ion, c is the speed of light and $\rho_{\rm crit} = 1.88 \times 10^{-29}\, h^2\, \mathrm{g\,cm^{-3}}$ is the critical density today. The redshift absorption distance $X(z)$ (Tytler, 1987) is defined as $X(z) = \frac{2}{3\Omega_{\rm m}}((\Omega_M(1+z)^3 + \Omega_\Lambda)^{1/2} - 1)$, which is valid for $\Omega_{\rm M} + \Omega_\Lambda = 1$. It is used to put the systems on a comoving coordinate scale by removing the redshift dependence. Under this definition, $f(N)$ is constant in redshift for systems with constant comoving space density and constant physical size. We adopted the associated fractional variance:

$$\left(\frac{\delta\Omega_{\rm C\,IV}}{\Omega_{\rm C\,IV}}\right)^2 = \frac{\sum_i [N_i(\mathrm{C\,IV})]^2}{[\sum_i N_i(\mathrm{C\,IV})]^2}, \qquad (2)$$

proposed by Storrie-Lombardi et al. (1996).

Fig. 1 illustrates the 13 NIRSPEC spectra of Table 1. They cover $\Delta X = 41.096$, which doubles the path length sampled in our previous analysis (Ryan-Weber et al., 2009). The redshift representative of the full sample is $z = 5.53^{+0.72}_{-0.39}$. We consider C IV systems with $\log(N_i(\mathrm{C\,IV})) > 13.8$ cm^{-2} , and calculate $\Omega_{\rm C\,IV} = 3.2 \pm 1.3 \times 10^{-9}$.

The distribution in wavelength of C IV systems (open circles in Fig. 1) could be biased due to the contamination from sky emission (bottom panel spectrum). Therefore, we adopted a conservative approach and removed the pixels affected by bright sky emission lines (grey regions in Fig. 1) from the calculation. The sky-corrected absorption path is $\Delta X' = 27.261$, which represents a decrease of ~ 33 % in redshift path but it only includes the most reliable wavelength sections. We removed two systems that could be affected by skylines at $z_{\rm abs} = 5.3229$ and $z_{\rm abs} = 5.6363$ in J0818 and J0927, respectively. The sky-corrected values of $\Omega_{\rm C\,IV}$ is $\Omega'_{\rm C\,IV} = 3.3 \pm 1.7 \times 10^{-9}$. Therefore, removing the most contaminated wavelength regions has not changed our result.

4. Discussion

Currently, observations suggest that $\Omega_{\rm C\,IV}$ decreases with redshift to $z \sim 6$ (D'Odorico et al., 2013). This is consistent with a progressive reduction, towards earlier cosmic time, of the ionized metal content of the CGM and/or a change in the ionization state of the metal-enriched gas. However, there is an open debate about the existence of a rapid decrease of $\Omega_{\rm C\,IV}$ at $z > 5$.

Ryan-Weber et al. (2009) measured $\Omega_{\rm C\,IV}$ at ~ 5.76 from nine lines of sight and four C IV systems observed with medium and low resolution spectroscopy (53 and 185 km s^{-1}). They reported a drop in $\Omega_{\rm C\,IV}$ of a factor of ~ 3.5 compared to the value from Pettini et al. (2003) at $z \sim 4.7$. However, one system that contained 38 percent of the C IV in the sample is a miss-identified Mg II absorption (Simcoe et al., 2011). As a result, using the three remaining C IV systems from Ryan-Weber et al. (2009), the corrected value of $\Omega_{\rm C\,IV}$ at $z \sim 5.8$ is $\sim$ 5–6 times smaller than its value for $z \leq 4.7$ (solid circle in

*`https://github.com/nhmc/plotspec.git`

**`http://www.ast.cam.ac.uk/$\sim$rfc/vpfit.html`

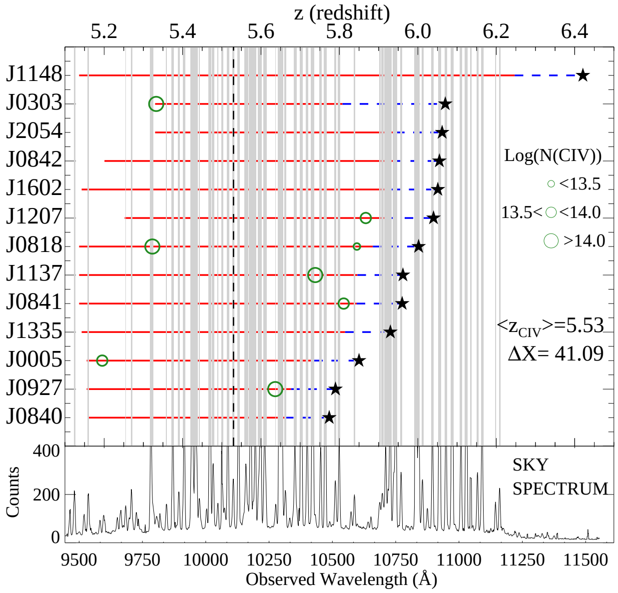

Figure 1: Representation of the absorption path of the lines of sight included in this work. Each sight-line is illustrated with a red line. The dashed portion of the line is either within 5000 km s^{-1} from the QSO or the spectrum does not have the required sensitivity. The open circles represent the C IV systems.

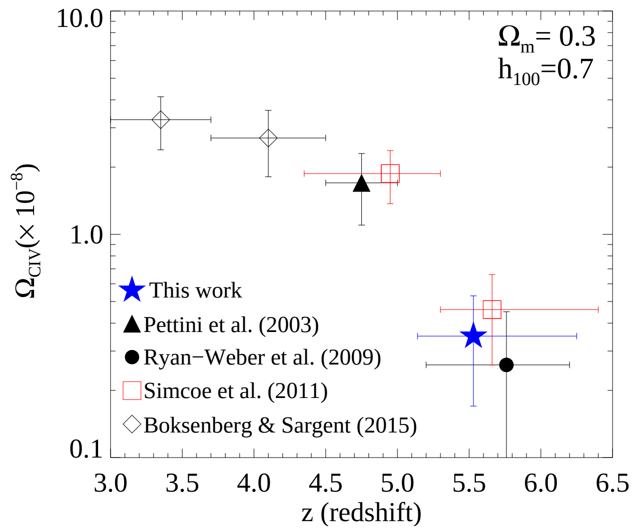

Figure 2: Evolution of $\Omega_{\rm C\,IV}$ as a function of redshift. The value from Pettini et al. (2003) (solid triangle) was taken from Ryan-Weber et al. (2009). The value from Ryan-Weber et al. (2009) at ~ 5.76 (solid circle) was corrected for a miss-identified Mg II absorption. Open diamonds are from Boksenberg & Sargent (2015).

Fig. 2). Both numbers are corrected for completeness for $\log(N(\mathrm{C\,IV})) > 13.8$ cm^{-2}.

The decline of $\Omega_{\rm C\,IV}$ at $z > 4.5$ was confirmed by Simcoe et al. (2011) using 13 lines of sight observed with different spectral resolutions (185, 50 and 23 km s^{-1}). They reported a drop of a factor of ~ 4 in $\Omega_{\rm C\,IV}$ from $z \sim= 4.95$ to $z \sim= 5.66$, based on systems with $13.4 < \log(N(\mathrm{C\,IV})) < 15.0$ cm^{-2}. In addition, D'Odorico et al. (2013) finds that $\Omega_{\rm C\,IV}$ at $z > 5.3$ is two times lower than its value at $z < 5.3$, but the result depends on the range in $N(\mathrm{C\,IV})$ included in the calculation.

Detection of C IV depends on the metallicity and the ionization state of the absorbing gas. Therefore, if confirmed, a rapid change in $\Omega_{\rm C\,IV}$ at $z \sim 5.3$ could indicate a change in the metal content or in the radiation field. On one hand, this could be a critical moment in the chemical evolution of the Universe when the dominant mechanism of enrichment is changing. On the other hand, space fluctuations predicted to exist in the ionizing flux density (background radiation) during the tail-end of the epoch of reionization could also be responsible of a drop in $\Omega_{\rm C\,IV}$ on a short time scale. The answer is probably a combination of both effects.

Our measurement of $\Omega_{\rm C\,IV}$ is consistent with previous results. From a sample of seven systems in 13 lines of sight our current measurement of $\Omega_{\rm C\,IV}$ at $z \sim 5.53$ suggest a decrease of a factor of ~ 5 from $z \sim 4.8$. However, this work is in progress and it has not been corrected for completeness. This effect and other sources of uncertainty will be considered in a forthcoming paper where we will discuss the implications of a rapid evolution in $\Omega_{\rm C\,IV}$ at $z > 5$ and the significance of this result.

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