Heavy element enrichment in the IGM at high redshift

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Abstract. We present a detailed analysis of the ionisation state and heavy element abundances in the Intergalactic Medium (IGM). The CIV doublet is shown by 30% of the 182 selected optically thin Lyα clouds in 10 QSO lines of sight. Direct metallicity calculations have been performed on individual systems with detected CIV and SiIV (10% of the sample) varying the UV photoionising source, cloud density and size and silicon relative abundance. The best solutions for carbon content in this subsample (redshift coverage \( z = 2.6 \) – 3.8) span between 1/6 and 1/300 of the solar value with no evidence of redshift evolution in both the metallicity and the ionising source. Global properties of the whole sample indicate that the metallicity in Lyα clouds with CIV and SiIV is not typical of the IGM. The redshift evolution of the UVB is one of the possible sources of the observed SiIV/CIV trend presented by Cowie and collaborators during this meeting. Future detection of heavy elements in lower HI column density (log \( N_{\text{HI}} \) < 14.5) Lyα clouds relies on the presence of OVI and NV at \( z = 1 \) – 2.5.

1 Introduction

For many years the Lyα forest has been considered a different class of objects with respect to galaxies. The available sensitivity was too low to detect any sign of non–primordial composition in the intergalactic gas clouds at high redshift. Thanks to the advent of high resolution and signal–to–noise spectroscopy, the old idea on the majority of quasar absorption lines has been revisited and opened in the last few years a still pending debate on the connection between the Lyα forest and the galaxy formation of the early Universe. The detection of ions different from CIV in optically thin Lyα clouds is made complicated by harder observational conditions, whereas the still too poor knowledge of the ionisation mechanisms which determine the ion abundances in those clouds has often discouraged attempts of metal content estimations as a function of redshift and of HI column density. However abundance investigation of the Lyα clouds has fundamental implications in the understanding of the enrichment processes in the IGM by Pop III stars in the \( z > 5 \) Universe.

2 Metallicity measurements

The sample of optically thin absorption lines with \( 14.5 < \log N_{\text{HI}} < 16.5 \) has been obtained by high resolution spectroscopy, mainly HIReS/Keck (Songaila 1997b) but also by EMMI/NTT for the \( z \geq 3.7 \) systems (Savaglio et al. 1997). For all the systems CIV and/or SiIV and CII detections or upper limits are given in redshift coverage \( 2 < z < 4.5 \). The lower bound in \( N_{\text{HI}} \) is due to the very rare metal detection in lower column density systems. In this range even
if the line can be saturated (depending on the Doppler width) Monte Carlo simulations showed that fitting procedures of synthetic individual lines with similar resolution and S/N ratio of the observed spectra give HI column density errors which are less than a few tens of dex (for $b = 25$ km s$^{-1}$, log $N_{\text{HI}} = 15.5$, FWHM = 12 km s$^{-1}$and S/N = 20 this is typically 0.1 dex). The blending effect has a much more dramatic impact on column density uncertainties and for this reason, we consider in the case of complex structures as an individual cloud the total column densities of HI and of metal lines.

Estimating the heavy element content in the Ly$\alpha$ clouds is mostly complicated by the poor knowledge of the ionising sources. As a first simplification, we assume that this is dominated by photoionisation of the UV background and neglect any other mechanism. Collisional ionisation is important when the gas temperature exceeds $10^5$ K. At that temperature, the Doppler parameter for HI is 41 km s$^{-1}$, well above the mean value typically found in Ly$\alpha$ clouds. The analysis of metal lines in Ly$\alpha$ clouds (Rauch et al., 1997) shows that the mean “Doppler” temperature in these clouds is $\sim 4 \times 10^4$ K, making any evidence of collisional ionisation hard to justify. Once the photoionisation equilibrium is assumed, we first consider the subsample of Ly$\alpha$ clouds which show both CIV and SiIV absorption. To calculate the metallicity we use CLOUDY and assume six different shapes for the UV background normalized to the value at the Lyman limit ($J_{912} = 5 \times 10^{-22}$ erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ sr$^{-1}$) changing the parameter $S_L = J_{912}/J_{228}$ in the range 200 – 3000. We varied the [C/H] and gas density in such a way to reproduce the observed CIV. We also assume the relative silicon–to–carbon abundance to be between 0 and three times solar and consider the cloud size along the line of sight to be in the range 1 kpc $\lesssim R \lesssim 50$ kpc. Given these assumptions, we obtain for this subsample a set of 18 [C/H] measurements shown in Fig. 1. Carbon abundance in clouds with detected carbon and silicon has a large spread with mean values of [C/H] = $-1.8$ and no evidence of redshift evolution. We notice that this sample might consist of metal–rich Ly$\alpha$ clouds since it has been selected because of the SiIV detection and might not be representative of the whole population of Ly$\alpha$ clouds. In a
Figure 2: Ion column density ratios as a function of redshift. Solid curves are models assuming the UVB as described by the first two panels (log $N_{\text{HI}} = 15$ and $[\text{C/H}] = -1.8$). Dashed curves are the same but for $[\text{C/H}] = -1.8 \pm 0.8$.

Recent work, Songaila (1997a) has estimated the total universal metallicity at $z \sim 3$ (assuming that at that time the baryonic matter of the Universe mostly resides in the Lyα forest) to be in the range 1/2000 and 1/630 relative to solar.

In a different approach, we consider the whole sample and regard the global observed properties instead of the individual systems and compare with models. Results of column density ratios on the $z$ and $N_{\text{HI}}$ planes are shown in Figs. 2 and 3. In Fig. 2 we investigate the redshift evolution of observed column densities in the case of $S_L$ and $J_{912}$ as reported. The discussed trend of SiIV/CIV (Cowie et al., this conference proceedings) can be reproduced by a redshift evolution of $S_L$ from 200 at $z \sim 2$ to 3000 at $z \sim 4$. The same model can take into account other observed ion ratios. In Fig. 3 we compare observations with CLOUDY models assuming that all the clouds of the sample are at the same mean redshift of $z = 3$ with $S_L = 800$ and the gas density proportional to the square root of $N_{\text{HI}}$, as given in the case of spherical clouds in photoionisation equilibrium with the UVB. In both figures the solid lines are obtained for metallicity $[\text{C/H}] = -1.8$ and $[\text{Si/C}] = [\text{O/C}] = 0.5$, $[\text{N/C}] = 0$. Models of photoionisation equilibrium can include the majority of metal detections (also considering the metallicity spread) but CII/HI which, as function of $N_{\text{HI}}$, looks to be steeper than calculated. Additional observations of
Figure 3: Ion column density ratios as a function of HI column density. Solid and dashed curves are model calculations assuming the UVB at $z = 3$ of Fig. 2 ($[\text{C/H}] = -1.8 \pm 0.8$). Straight lines represent detection limits.

CII would probably cast further light on the discussion on the ionisation state and metal content in the Ly$\alpha$ clouds. In both figures, the numerous upper limits falling below the dashed curve $[\text{C/H}] = -2.6$ is an indication that in many clouds the metallicity is lower than the values found in the selected sample.

3 The future

The investigation of low and intermediate redshift ($z = 1 - 2.5$) observations of OVI and NV in $\log N_{\text{HI}} \lesssim 14$ Ly$\alpha$ clouds might succeed in answering the question of how efficient the mixing processes in the IGM at high redshift has been. Relative abundances can provide new hints on the study of metal production by Pop III stars. In particular NV since it has been predicted to be underproduced in massive stars with low initial metallicity (Arnett 1995). More observations of the SiIV/CIV ratio for $z < 2$ and $z > 4$ are a challenging probe of the redshift evolution of the UVB, though this can be one of the many possible reasons for the observed SiIV/CIV trend (another would be redshift evolution of the gas density being lower at lower redshift). More interesting conclusions await outcomes from new high quality data of Keck observations.

References

[1] Arnett D., 1995, ARA&A, 33, 115
[2] Rauch M., Sargent W.L.W., Womble D.S., Barlow T.A., 1997, ApJ, 467, L5
[3] Savaglio S., Cristiani S., D'Odorico S., Fontana A., Giallongo E., Molaro P., 1997, A&A, 318, 347
[4] Songaila A., 1997a, ApJL, in press, astro-ph/9709046
[5] Songaila A., 1997b, in preparation