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Clues to the origin of metals in the Lyα forest

S. LOPEZ[1], S. D'ODORICO[2], S. L. ELLISON[2,3] and T.-S. KIM[4]
(1) Universidad de Chile, Chile
(2) European Southern Observatory
(3) Pontificia Universidad Católica de Chile, Chile
(4) Institute of Astronomy, UK

Abstract

We analyze the $z = 2$ Lyα and C IV forest along two adjacent lines-of-sight at high S/N and spectral resolution to assess the question of the origin of metals in the intergalactic medium. We find that the gas containing detectable amounts of metals (as seen in absorption by C IV) is less quiescent on scales of a few kpc than the gas without metals. Although it is difficult to discriminate unequivocally between possible sources of enrichment and the extent to which each contributes to line-of-sight differences, those suggest that the metal-enriched systems are bound to galaxies (i.e., they do not arise in the IGM nor in galactic winds).

1.1 Introduction

The high-z IGM is inhomogeneously distributed on large-scales in voids and filaments; it contains a large fraction of baryons (Rauch, Haehnelt & Steinmetz 1997) and is highly ionized and warm ($\sim 10^4$ K). Despite a low neutral fraction, a large range of densities —from slightly underdense gas up to the denser environment of collapsed objects— can be probed via H I absorption of photons from background QSOs. This is called the Lyα forest. The optical depth of the H I, $\tau_{\mathrm{Ly}\alpha}$, maps overdensities in the low density regime. The higher the H I column density, the stronger and kinematically more complex the system.

High $N_{\mathrm{H\,I}}$ absorbers, $N_{\mathrm{H\,I}} \gtrsim 10^{16}$ cm^{-2}, contain heavy metals (the C IV $\lambda\lambda 1548, 1550$ Å doublet is the most common and easy-to-recognize metal absorption feature). At low-z, strong C IV systems arise in galactic halos (e.g., Chen et al. 2001; Heckman et al. 2000). Low $N_{\mathrm{H\,I}}$ absorbers, on the other hand, with $N_{\mathrm{H\,I}} \lesssim 10^{14}$ cm^{-2}, contain no metals, or we lack of sensitivity to detect them (Cowie & Songaila 1998; Ellison at al. 2000). A fraction of *intermediate* $N_{\mathrm{H\,I}}$ absorbers, however, with $10^{14} \lesssim N_{\mathrm{H\,I}} \lesssim 10^{16}$ cm^{-2}, does show weak C IV at a level of $W \sim$ a few mÅ (Cowie et al. 1995). For these absorbers simple photoionization models have given a metallicity of $Z = 0.1 - 1$ % solar (Carswell, these proceedings).

Here we asses the question of the origin of such metals. Possible and non-exclusive models depend on when the metals were released to the IGM:

(1) Supernova-driven outflows from early galaxies with a small contribution from PopIII stars (e.g., Scannapieco, Ferrara & Madau 2002); however, only a fraction of the IGM can be metal-enriched through this mechanism (but see Ferrara, Pettini, & Shchekinov 2000).
(2) 'In situ' or more recent enrichment by galactic winds (Theuns et al. 2002); however, metals are difficult to transport over large distances.

Our aim in this work is to check the different enrichment hypotheses by observing the Lyα

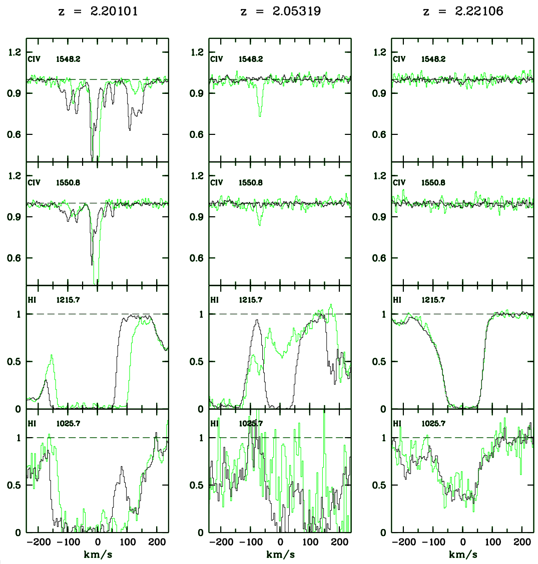

Fig. 1.1. Examples of absorption systems in HE1104−1805 A (black) and B (grey). *Left:* a 'complex' metal system with several velocity components. *Middle:* a 'single component' metal system observed in B only. *Right:* a saturated H I system with no C IV detected. Separation between LOS is only 0.6 h_{50}^{-1} kpc. H I column densities (left to right): $N_{\rm H\,I} > 9.3 \times 10^{16}$, 1.0×10^{15}, and 3.0×10^{14} cm^{-2}

and C IV forests along two adjacent lines-of-sight (LOSs). The idea is to study the possible observational effects that feedback from star formation might have in the two spectra. One difficulty inherent to this approach is that the gas in the Lyα forest is mostly ionized, meaning that either the gas metallicity Z, or the density $n_{\rm H}$ is a free parameter when modeling the ionization balance. In addition, the information on H I is inaccurate for $N_{\rm H\,I} \gtrsim 10^{14.5}$ cm^{-2} because the Lyα lines become saturated.

1.2 Results

1.2.1 Data

For the first time we have obtained simultaneous coverage of the Lyα and C IV forests at high S/N and resolution (VLT-UVES) along two closely separated LOSs (the gravitationally lensed QSO HE1104−1805). The redshift range for Lyα *and* C IV is $z = 1.6$ to $z = 2.3$. The quality of the spectra allows us to detect C IV systems down to $N_{\rm CIV} = 10^{11.8}$ cm^{-2}. The observed distribution of systems per unit column density, when compared with that of Ellison et al. (2000), implies that our sample is complete down to $N_{\rm CIV} = 10^{12.3}$ (A) and $10^{12.5}$ (B) cm^{-2}. Typical separation between LOSs is 2 h_{50}^{-1} kpc. At this separation, we expect totally correlated Lyα forest spectra (Smette et al. 1995).

1.2.2 Approach 1: line profile fitting

All lines in the Lyα forest were profile-fitted with VPFIT automatically, and self-consistent solutions for 872 Lyα systems —half of them also with simultaneous fits to Lyβ—

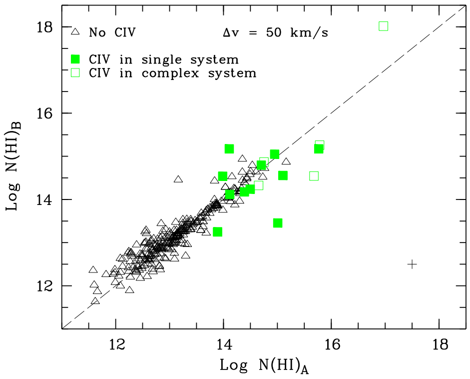

Fig. 1.2. H I column density of Lyα forest systems in HE1104−1805 A and B, with C IV in either or both spectra (gray squares) and without C IV (black triangles). Open squares are for velocity components within complex systems; filled squares are for 'single' systems. The cross indicates the typical 1σ error.

were found. At each $z_{\rm HI}$ we searched for C IV, finding 93 C IV doublets in either spectrum. The H I and C IV fit processes were kept totally independent, which is important with regard to line positions (a redshift offset between C IV and H I is not unexpected; Ellison et al. 2000). Since many velocity components can be present (Fig. 1.1), we attempted an automatic association of C IV with a certain H I system by summing up all VPFIT column densities within a given velocity window. This procedure also minimizes the effects of line blending and redshift offsets. If C IV was present within $\pm\Delta$ km s^{-1} of $z_{\rm HI}$, we made the distinction between (1) complex, strong and clustered systems and (2) single, weak and isolated systems.

Fig. 1.2 shows a comparison of $N_{\rm H\,I}$ along both LOSs for $\Delta = 50$ km s^{-1}. We observe that $N_{\rm H\,I}$ shows in general stronger variations across the LOSs in H I+C IV systems than in H I-only systems within the same range of $N_{\rm H\,I}$ (the scatters of the column density differences are respectively $\sigma_{\rm HI+CIV} = 0.7$ dex and $\sigma_{\rm HI} = 0.4$ dex). Note that any effect of disturbed gas will be less evident here because possible velocity shifts are not considered when comparing column densities. Therefore, *the general trend seems to be that of* $N_{\rm H\,I}$ *varying more strongly across the LOSs when* C IV *is present.*

If we consider every C IV system, we find (Fig. 1.3, left panel) that single and complex systems both span a similar range of C IV/H I ratios and that, moreover, there is little distinction between both classes. The C IV/H I ratio is a function of both gas density (thus of ionization) and metallicity, but the correlation between C IV/H I and H I that is observed here rather points out to density variations (ionization) as the main source of spread. Ionization parameters in the range $\log U = -3$ to $\log U = -1$ reproduce the observed range of C IV/H I values for $Z = 0.1$ solar. Altogether, *complex and single systems seem to share similar physical properties and thus to have a common origin*.

If we investigate the *transverse* differences in C IV/H I between LOSs we find that they do not correlate with C IV/H I (right panel of Fig. 1.3). Under the assumption of homogeneous metallicity, the lack of a trend may be connected to the mechanism of metal transport. Consider, for example, the observed metals as having been produced in far galaxies

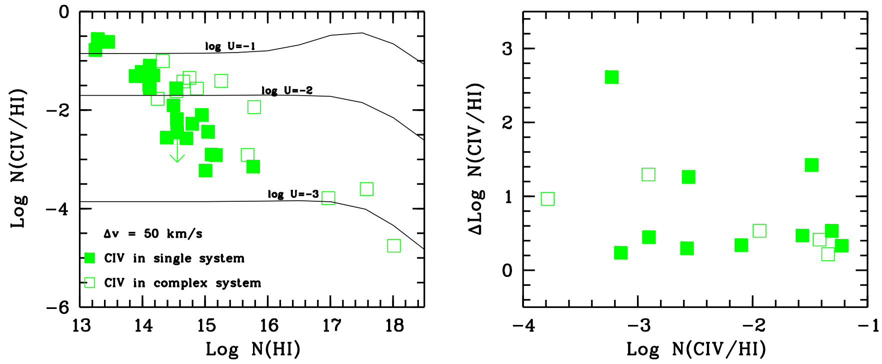

Fig. 1.3. *Left:* C IV/H I ratio vs. $N_{\rm H\,I}$ for all systems (A and B) along with CLOUDY photoionization models for $Z = 0.1$ solar, a Haardt & Madau (1996) ionizing background spectrum and different ionization parameters U. *Right:* variation of the C IV/H I ratio across the LOSs as a function of C IV/H I.

and transported by strong galactic outflows that *ionize* their surroundings (Adelberger et al. 2003; Kollmeier et al. 2002). Then, the stronger the wind, the more ionized the gas (higher C IV/H I), and —simultaneously— the more perturbed the medium (larger ΔC IV/H I). Therefore, and despite of the small sample, it seems that the observed C IV is *not* part of strong galactic outflows.

1.2.3 Approach 2: Pixel counting

As an alternative to column densities, the optical depth per pixel $\tau_{\rm Ly\alpha} = -ln(F)$, where F is the normalized flux, was calculated for each spectrum. Differences $\Delta\tau$ between the A and B spectra, and their median values $< \Delta\tau >$ were calculated over $\pm\Delta$ km s^{-1} around each $z_{\rm Ly\alpha}$. Fig. 1.4 shows $< \Delta\tau >$ as a function of τ for $\Delta = 100$ km s^{-1} (to account for slightly saturated lines, the velocity window was larger than in 1.2.2). Mock spectra constructed to evaluate the accuracy of the $\Delta\tau$ measurement indicate that $\Delta\tau$ is confidentially well constrained if $\tau \lesssim 3$. Also here we observe that $\tau_{\rm Ly\alpha}$ has more structure around H I+C IV systems than around H I-only systems. We argue that in this plot the effect is more striking than in Fig. 1.2 because of radial velocity shifts in systems that contain C IV.

1.3 Conclusions

Our conclusions are twofold. First, the H I at $z = 2$ seems to be more inhomogeneous if it hosts C IV, on scales for which the forest is otherwise featureless. Velocity shear appears to be main driver for the observed differences but changes in ionization might be also significant. Secondly, we find that weak C IV systems in the intermediate $N_{\rm H\,I}$ forest do not differ much from single components in more complex C IV systems.

As a consequence, the weak C IV observed here can not simply be the relic of an early widespread episode of metal enrichment. Rather, the cross-talk between both H I spectra on such small scales is naturally explained by metal-enriched gas that is perturbed because it is bound to galaxies. While this is not a surprise for $N_{\rm H\,I} = 10^{16}$ cm^{-2}, it is interesting

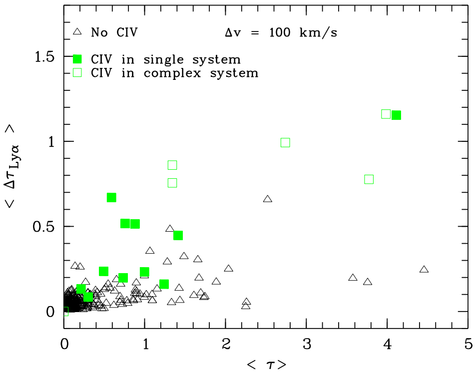

Fig. 1.4. Optical depth differences $\Delta\tau_{\mathrm{Ly}\alpha}$ between spectra within ± 100 km s^{-1} of $z_{\mathrm{Ly}\alpha}$ as a function of τ.

to see that the trend continues down to $N_{\mathrm{H\,I}} = 10^{14}$ cm^{-2} absorbers. Our finding builds on observations of Lyman-break galaxies capable of enriching and ionizing the IGM (Pettini et al.2001; Adelberger et al. 2002), and of C IV absorbers having been disturbed recently (Rauch, Sargent & Barlow 2001). However, it does not fit into hydrodynamical simulations that predict C IV-transporting galactic winds to have little effect on H I (Theuns et al. 2002).

The similar C IV/H I ratios in weak and strong systems is intriguing. Indeed, we may be simply lacking sensitivity to detect more structure along the line of sight. Thus, the possibility appears that the C IV in *moderate* column-density Lyα systems at $z = 2$ has a real 'in-situ' origin, occurring in the extended halos of an as yet undetected population of galaxies. Certainly this does not exclude the possibility that some of the detected systems might arise in the 'true' IGM. An increase of sensitivity and hence in the statistics of weak systems will help unveiling this longstanding problem.

References

Adelberger K. L., Steidel, C. C., Shapley, A. E. & Pettini, M. 2002, 584, 45
Carswell, R. F. 2003, Carnegie Observatories Astrophysics Series, Vol.4: Origin and Evolution of the Elements, ed. A. McWilliam and M. Rauch (Cambridge: Cambridge Univ. Press)
Chen H. W., Lanzetta, K. M. & Webb, J. K. 2001, ApJ, 556, 158
Cowie L. L. & Songaila A. 1998, Nature, 394, 44
Cowie L. L., Songaila, A., Kim, T.-S. & Hu, E. M. 1995, AJ, 109, 1522
Ellison S. L., Songaila, A., Schaye, J. & Pettini, M. 2000, AJ, 120, 1175
Ferrara, A. Pettini, M. & Shchekinov, Y. 2000, MNRAS, 319..539
Haardt, F., & Madau, P. 1996, ApJ, 461, 20
Heckman T. M., Lehnert, M. D., Strickland, D. K. & Armus, Lee 2000, ApJS, 129, 493
Kollmeier, J. A., Weinberg, D. H., Dave, R. & Katz, N. 2002, astro-ph/0212355
Pettini M., Shapley, A. E., Steidel, C. C., Cuby, J.-G., Dickinson, M., Moorwood, A. F. M., Adelberger, K. L., & Giavalisco, M. 2001, ApJ, 554, 981
Rauch, M., Haehnelt, M. & Steinmetz M. 1997, ApJ, 481, 601
Rauch M., Sargent W. L. W. & Barlow T. A. 2001, ApJ, 554, 823
Scannapieco, E., Ferrara, A., & Madau, P. 2002, ApJ, 574, 590
Smette A., Robertson, J. G., Shaver, P. A., Reimers, D., Wisotzki, L. & Koehler, T. 1995, A&AS, 113, 199
Theuns T., Viel, M., Kay, S., Schaye, J., Carswell, R. F. & Tzanavaris, P. 2002, ApJ, 578, L5