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THE SOURCE OF METALS IN THE HIGH-REDSHIFT LYMAN-α FOREST

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RESUMEN

El "bosque" Lyα frecuentemente exhibe líneas de absorción de elementos pesados, pero la fuente del enriquecimiento metálico aún no se entiende a cabalidad. Se presentan inigualables espectros de alta resolución de cuasares dobles por efecto de lentes gravitacionales que permiten estudiar la estructura de este gas altamente ionizado a escalas de 1 kpc. Los tamaños de los absorbentes que se derivan de nuestros datos restringen las condiciones de ionización y las abundancias relativas de CNO a $z \sim 2$. Éstas indican que el gas ha sido procesado más bien en galaxias y poco antes de que la absorción ocurriera, en contraposición a un enriquecimiento muy temprano ($z > 6$) por estrellas de población III.

ABSTRACT

The Lyα forest frequently exhibits associated metal absorption lines, but the source of metal enrichment is not fully understood yet. We present unique high-resolution spectra of gravitationally-lensed background quasars that has allowed us to study the kpc-scale structure of this highly ionized gas. The sizes of the absorbers derived from our data constrain both the ionization conditions and the CNO relative abundances at $z \sim 2$. These indicate that the gas has been processed in galaxies and recently before the absorption occured, rather than in a very early epoch ($z > 6$) by Population III stars.

Key Words: **INTERGALACTIC MEDIUM — QUASARS: ABSORPTION LINES**

1. HEAVY METALS IN THE Lyα FOREST

The Lyα forest seen in spectra of background quasars is the absorption signature of the intergalactic medium. At high-redshift ($z >\sim 2$) it contains a large fraction of the baryons (90%; Rauch, Haehnelt & Steinmetz 1997), and is warm ($\sim 10^4$) and highly (photo)-ionized. The Lyα forest was once supposed to contain primordial material unenriched by the products of star formation; however, since the advent of spectrographs on 8-10m-class telescopes, redshifted UV transitions by metals are frequently detected in the optical spectra of background quasars at $z_{\rm abs} = z_{\rm Ly\alpha}$. On the other hand, at lower redshifts, a population of O VI absorbers at $z \lesssim 0.3$ discovered by HST and FUSE have revealed predominantly collisionally ionzed gas at $T \sim 10^5$ K (e.g Tripp & Savage 2000), the so-called warm-hot intergalactic medium (WHIM). In principle, this gas could be detected only in high-ionization stages of abundant elements, most of them in the x-ray range but some, like O VI (IP = 138 eV), in the UV. Whether a WHIM at high-redshift exists, how those metals have been released to the IGM, and what keeps the gas ionized, all are key questions toward a better understanding of galaxy formation and evolution.

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2. THE NEW OBSERVATIONS

We present spatially-resolved high-resolution UVES VLT spectra of two lensed QSOs toward which we have detected O VI in 8 intervening and 3 "associated" ($z_{\rm abs} \approx z_{\rm em}$) absorption systems (Lopez et al. 2006). Their redshifts range between $z = 2.087$ and 2.633, and their O VI column densities between $10^{12.9}$ and $10^{13.9}$ cm^{-2}. We use the information provided by differences and similarities across the lines of sight in the line parameters of various species to extract physical parameters via photoionization models.

This is the first time that a direct measure of O VI sizes from gravitational lensing has been achieved. We have complemented our coherence scale limits derived from lensing with models of one and two phase ionized media. The combination of constraints from these two directions has allowed us to derive approximate sizes (under certain assumptions of the multiphase structure) and relevant abundances of C, N and O. Our conclusions were as follows.

1. All intervening O VI systems detected in one line of sight (LOS) show O VI also in the other. Within uncertainties, N(O VI) shows almost no structure across the LOS, and the data are consistent with a null fractional change. On the other hand, for 4 out of the 6 systems in which we detect also C IV, the

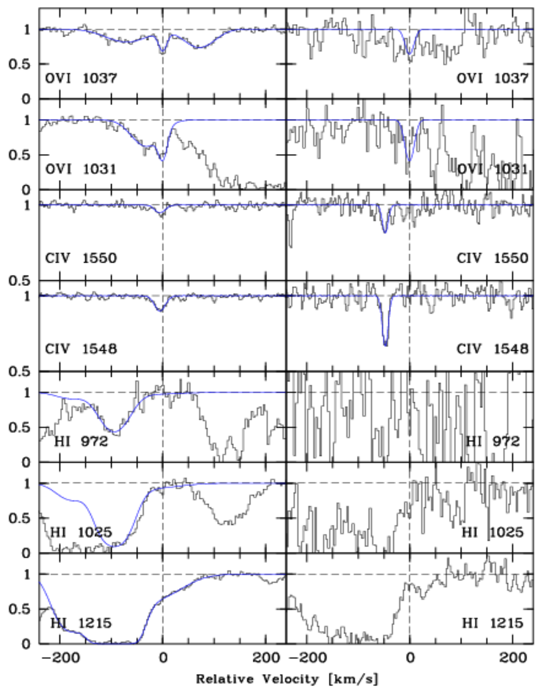

Fig. 1. Lefthand (righthand) panels show transitions observed along sightline A (B). The smoothed lines show Voigt profiles fitted to the data and used to obtain column densities and Doppler parameters. In both panels the vertical dashed line indicates $z = 2.437271$, which is the redshift of O VI in the A spectrum. The sightlines are separated by 1.4 h_{70}^{-1} kpc at this redshift. Note the velocity offset between the C IV absorbers along sightline A and B, not seen in O VI.

fractional change in the latter is significant between the LOS (up to 60%).

2. C IV and O VI systematically show velocity offsets between line centroids. There are also significant velocity offsets in C IV between LOS, but none of the O VI systems show such offsets. Doppler widths indicate photoionized gas, and these also do not show transverse variations.

3. The observed properties of species in the 2 LOS support a scenario in which an important fraction of C IV may not reside in the same volume as O VI. A two-phase model in which C IV arises both in a low and a high-ionization regime, with characteristic sizes of a few tens and a few hundreds of kpc, respectively, successfully explains the various LOS differences.

4. The observed O VI puts constraints on abundances, and photoionization requires for these clouds CNO abundances consistent with gas processed in galaxies recently before the absorption epoch. This implies that the absorbing gas is likely dominated by some kind of galactic feedback and/or it occurs not too far away from star-forming regions, although the observed O VI is of a very different nature than in the Galaxy. In particular, one system at $z = 2.437$ is consistent with the lines of sight crossing a metal-rich galactic outflow. However, from its kinematics across the LOS, O VI does not seem to be transported in the expelled gas.

Correlations between galaxies and metal systems at $z = 2-3$ have recently shown that O VI is always found at distances of up to a few hundred kpc from an observed galaxy (Adelberger et al. 2005). Our constraints on characteristic absorber sizes and relative abundances from photoionization models *and* on sizes and kinematic properties from observed transverse differences all fit well into a scenario of galaxy feedback. The extended O VI-phase we have detected here, though quite homogeneous on kpc scales, apparently is dominated by metals that have been put in place only recently by Type II SNe, in contrast to – or on top of – an early wide spread by Pop III stars. If the gas is able to escape galaxies and pollute the IGM up to large distances, this process may result in an inhomogeneous metal enrichment as suggested by simulations (e.g., Aguirre & Schaye 2005). We may have detected a new signature of this process in the disturbed C IV that is associated with the O VI systems. However, the dissociation between C IV and O VI observed here (both along and accross the LOS) is somewhat uncomfortable within that simple picture and may also indicate that the possible outflows required to transport the metals have different time scales for the different species (and thus ionization stages) , with O VI having been "in place" well before C IV. What fraction of the observed O VI indeed comes from galaxy feedback – in contrast to arising in pre-enriched gas – remains to be investigated for example with similar observations of binary QSOs to probe larger scales.

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