The Spatial Distribution of CIV in the Intergalactic Medium

M. M. Pieri
Université Laval, Québec QC, G1J 7P4, Canada; Imperial College London, Prince Consort Road, London, SW7 2AZ, UK
J. Schaye
IAS, Einstein Drive, Princeton, NJ 08540, USA
M. G. Haehnelt
IoA, Madingley Road, Cambridge CB3 0HA, UK
A. Aguirre
UC, Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, USA

We investigate the impact of environment on metal absorption observed in the Lyman α forest. Weak CIV absorption in spectrum of Q1422+231 is searched for using pixel correlation techniques in regions of the spectrum close to and far from galaxies at $z \sim 3$. This is achieved both using strong CIV absorption as a proxy for the presence of galaxies near the line of sight and by using the positions of observed Lyman break galaxies. We find that much of the carbon abundance is dependent not only on the HI optical depth and so gas overdensity but also proximity to highly enriched regions. Furthermore, most CIV absorption detected appears to be far from galaxies. This will improve constraints on models of feedback and the evolution of the intergalactic medium and galaxy formation.

1. INTRODUCTION

The spatial distribution of metals in the intergalactic medium (IGM) is a central indicator for feedback and galaxy formation since metals are not produced in situ in the low to moderate density IGM. Widely distributed metals are indicative of widespread and early feedback, whilst if metals are limited to the halos of galaxies, late feedback or inefficient mixing is implied.

The pixel correlation search for metals in the IGM in its simplest form involves collating Lyman α forest pixels in quasar absorption spectra and pairing them with the pixels where absorption by a chosen metal species is expected [1], [2]. In this case we search for absorption by triply ionized carbon (1548Å, 1551Å) - the most readily observed metal species seen in the Lyman α forest. A variety of techniques are employed to minimise contamination and maximise the information derived in order to arrive at a dependence between neutral hydrogen optical depth and apparent CIV optical depth.

Information regarding the redshift and density dependence of this enrichment has been derived using this search method and we modify it for the purpose of inclusion of environmental factors. We search for weak CIV both near and far from strong CIV absorption lines and both near and far from Lyman break galaxies (LBGs). This search is performed on the absorption spectrum of Q1422+231, observed with the HIRES instrument on Keck I. As with previous searches for CIV using this spectrum the absorbing gas considered is between $2.9 < z < 3.6$.

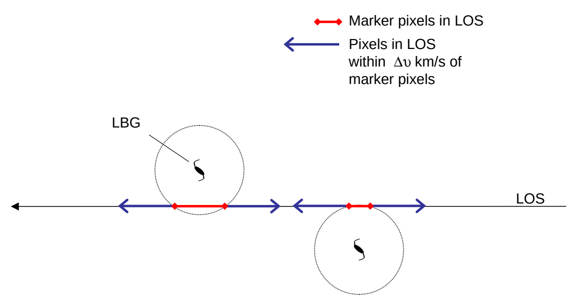

Figure 1: An illustration of the separation of the pixels into markers for LBGs near to the line of sight (LOS), the sample of pixels within a velocity ,Δv, of these markers and the sample of pixels corresponding to the rest of the spectrum.

2. TWO SAMPLES OF PIXELS

Strong CIV absorption in quasar spectra is believed to be correlated with galaxies close to the line of sight (LOS). The absorption seen in a number of quasar spectra has been compared with the redshifts of LBGs at small angular separations [3]. They conclude that where LBGs are particularly close to the LOS (within $\sim 0.5\mathrm{h}^{-1}$ Mpc comoving) the strongest CIV systems ($\mathrm{N}_{\mathrm{CIV}} \gtrsim 10^{13.5}\mathrm{cm}^{-1}$ or peak $\tau \approx 0.8-0.9$) are seen and that most systems found through line fitting are within $2.4\mathrm{h}^{-1}$ Mpc comoving of an LBG. Q1422+231 is the highest signal-to-noise spectrum in their sample.

We use strong CIV absorption as a proxy for galax-

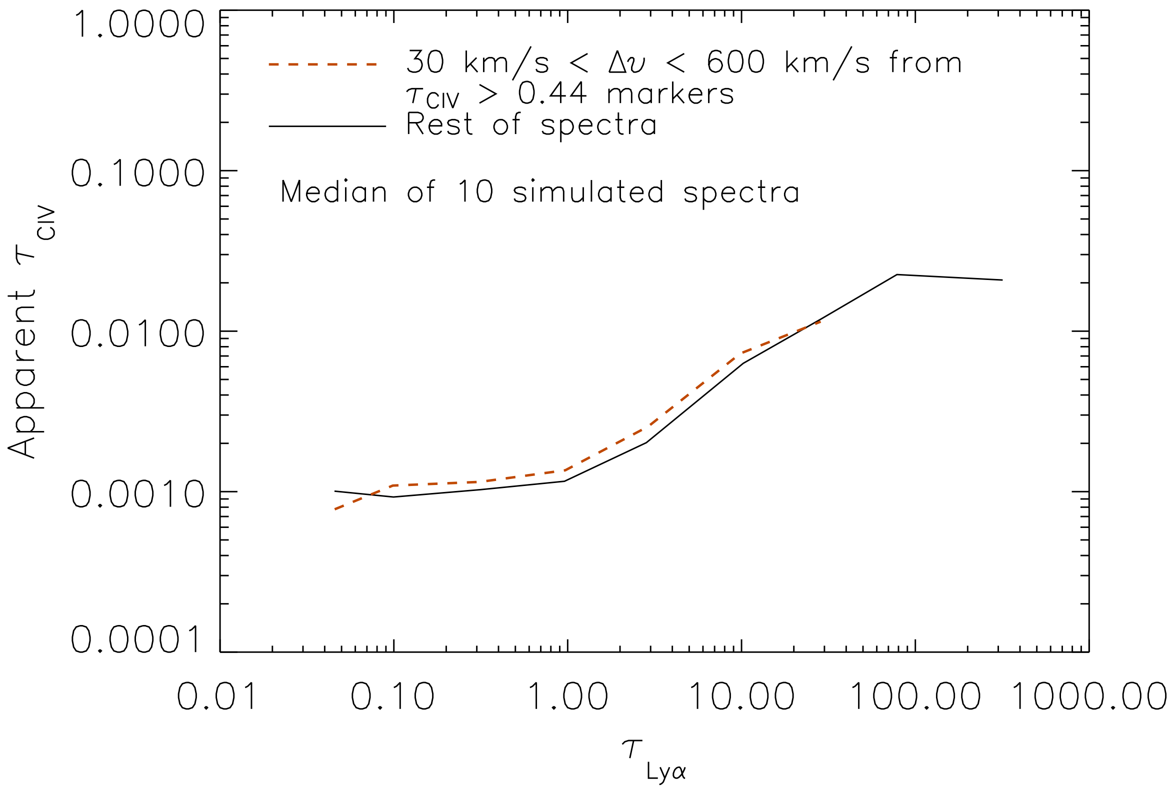

Figure 2: $\tau_{\mathrm{Ly}\alpha}$ - apparent τ_{CIV} relation for 10 simulated spectra derived using the two sample pixel correlation search for CIV. The curves shown are medians from the 10 spectra. The sample corresponding to pixels from the environments of galaxies are 10% of the total.

ies close to the line of sight. We take such pixels to be markers and separate our sample of HI-CIV pixel pairs into two sub-samples: those within a velocity, Δv, of these markers and the rest of the pixel pairs [6]. This is illustrated in Figure 1.

Where the optical depth of CIV pixels is above some threshold level, $\tau_{\mathrm{CIV,Thresh}}$, this pixel is flagged as a marker and pixels within Δv of this are searched for weak CIV absorption. The marker pixel itself is rejected from the search in order to avoid any difference between the two samples resulting from a trivial consequence of the search method. To further strengthen this claim we discard pixels within 30kms^{-1} of marker pixels (redward and blueward) and thus discard any contribution from the broadened wings of these strong CIV lines.

We have also used the redshifts of previously observed LBGs [4] near the line of sight to Q1422+231. LBGs within a chosen distance of the line of sight are used to separate the full sample of pixels into those within a velocity, Δv, and the rest of the pixels.

3. STRONG CIV ABSORPTION AS A PROXY

There are too few systems of peak $\tau_{\mathrm{CIV}} \gtrsim 0.8$ in an observed sample of one QSO absorption spectrum. However, we use the claim that other C IV lines found are close to LBGs and so while the markers may not be the same systems as LBGs, they are expected to be in their vicinity.

For a given Δv we choose the $\tau_{\mathrm{CIV,Thresh}}$ to provide a given fraction of pixels. Shown here are the results from a search with 10 % of pixels in the environment of strong CIV for both the spectra of Q1422+231 and the simulated spectra. For Δv = 600kms^{-1} this is provided by a $\tau_{\mathrm{CIV,Thresh}} = 0.44$.

This search method is tested with 10 simulated spectra [5] with overall and density dependent abundance consistent with pixel searches for gas along the line of sight to Q1422+231. Although the simulated spectra were formed with a scatter in the metallicity that matches previous observations, the scatter is not spatially dependent. It is apparent from Figure 2 that this search method does not distinguish between the two samples for the simulated spectra to a significant

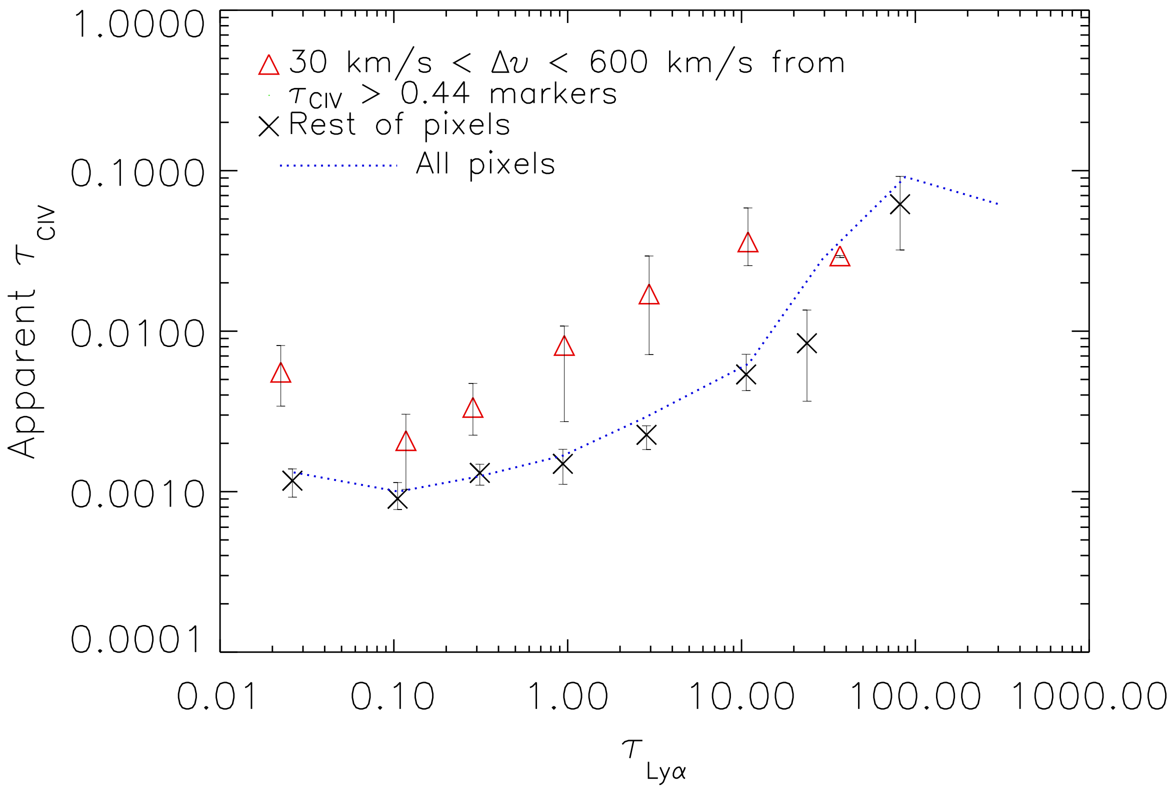

Figure 3: $\tau_{\mathrm{Ly}\alpha}$ - apparent τ_{CIV} relation for Q1422+231 derived using the two sample pixel correlation search for CIV. Strong CIV absorbers are used as a proxy for nearby galaxies The sample corresponding to pixels from the environments of galaxies are 10% of the total. The relation for all pixels is shown for comparison.

degree. This is as expected since the simulations do not contain patchiness and further supports our claim that this search method is sensitive to such patchiness.

The relation between apparent CIV optical depth and Lyman α optical depth is shown in Figure 3 for the IGM along the line of sight to Q1422+231. Using strong CIV markers the results of a search for weak CIV absorption is shown for both samples near and far from LBGs. For comparison the search results for the full sample of pixels is also shown.

It is apparent that we have succeeded in selecting two classes of objects since the relation between CIV and HI absorption differs significantly for the two samples. The difference is larger than may be explained as merely an artifact of the search method. This is consistent with observations that a large scatter in the [CIV/HI] is seen [5], [6] and indicates that this scatter may, in part, be a result of proximity to galaxies.

The observed metal enrichment is not confined to those regions near strong CIV absorption and so it does not appear that the enrichment is limited to the vicinity galaxies. This result is, however, dependent on the assumption that all galaxies near the line of sight are located using this technique.

The difference between the search for pixels far from galaxies and the full sample of pixels is small. Our understanding of the properties of the low-to-moderate density IGM away from galaxies may need to be adjusted by even small changes in the $\tau_{\mathrm{Ly}\alpha}$ - apparent τ_{CIV} relation. This result may also weaken limits on the already poorly constrained volume filling factor of metal enriched gas [7], [6] which is highly sensitive to the curve at $\tau_{\mathrm{Ly}\alpha} \sim 3$.

4. LBGS AS MARKERS

We also use a more direct approach for the investigation of regions in proximity to galaxies by taking redshifts and impact parameters of LBGs near Q1422+231 previously observed [4]. Again we separate our sample of pixels into two depending on whether the velocity offset from the nearest marker pixel is smaller/greater than $\Delta\upsilon$.

In Figure 4 we take $\Delta\upsilon = 600\mathrm{kms}^{-1}$ and a distance of $2.4\mathrm{h}^{-1}\mathrm{Mpc}$ comoving. This comoving distance from LBGs is the scale for which it is claimed [3] that most

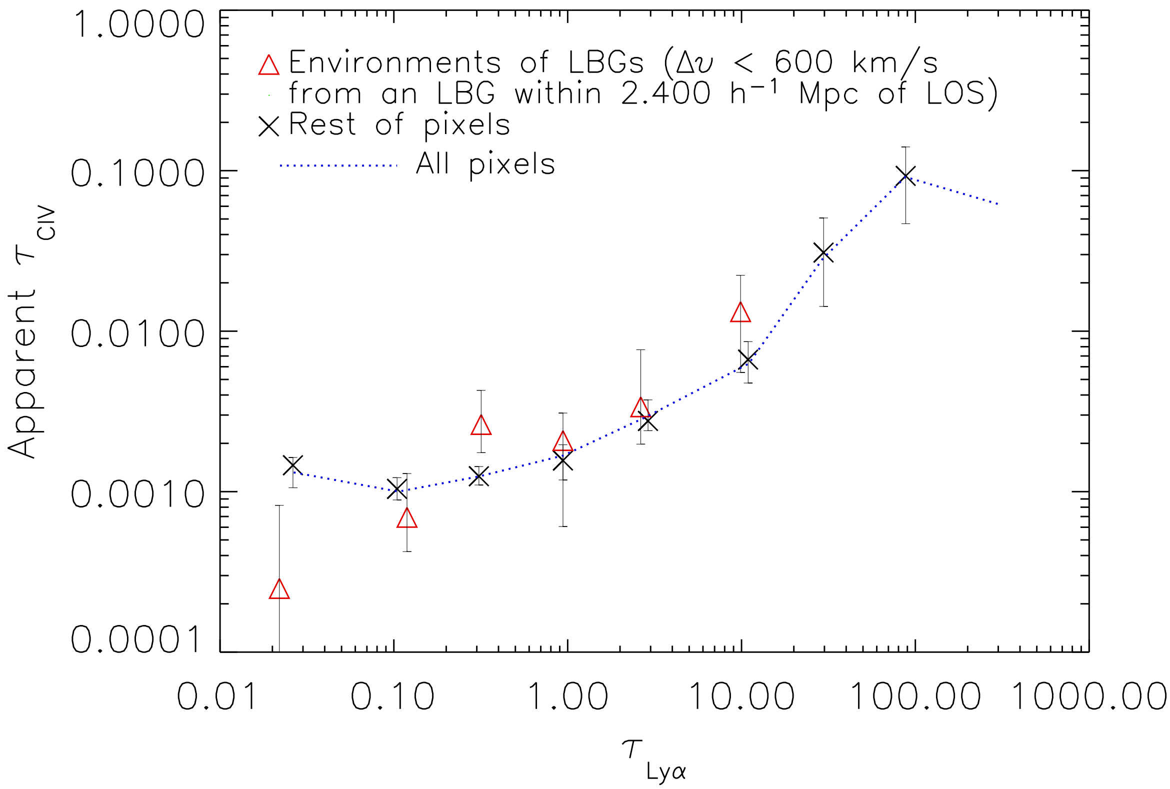

Figure 4: $\tau_{\mathrm{Ly}\alpha}$ - apparent τ_{CIV} relation for Q1422+231 derived using the two sample pixel correlation search for CIV. Positions of LBGs close to the line of sight (LOS) are used as markers for the separation of pixels into two samples. The relation for all pixels is shown for comparison.

of the CIV they detect are seen. 7 LBGs with corrected redshifts from Lyman α emission, interstellar lines or a combination of both are within this distance from the line of sight. These parameters result in 13% of pixels falling into the sample pixels in the environments of LBGs.

Using LBG positions as markers there is only a small, statistically insignificant difference in the CIV enrichment of the two samples. There may be a contradiction here since it has been claimed [3] that CIV absorption is correlated with LBGs in excess of that expected from large scale structure and clustering. We find there is clearly much CIV in regions away from known LBGs. This may be resolved by a difference in selection effects; they find that as much 4/5 of LBGs in the vicinity of CIV absorption systems may be absent from their catalogue due to the photometric selection criteria. Perhaps more significantly, we find more weak CIV absorption using the pixel search method and much of the absorption seen far from LBGs may be weak.

5. SUMMARY

- The abundance of carbon in the intergalactic medium is not only a function of density and redshift but also a function proximity to highly enriched regions.

- The observed signal is not an artifact of the search method as indicated by the use of simulated spectra.

- Where observed LBGs are used as markers to separate our sample of pixels into two, these samples do not appear to reflect different classes of absorbers.

- Using observed LBGs and highly enriched regions, it would appear that weak CIV absorption is not only limited to regions in proximity to galaxies.

Acknowledgments

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