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Enrichment Patterns of Heavy Elements in the Tenuous IGM

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Abstract

We describe the results of a heavy element census of the Intergalactic Medium at $z \sim 2.5$, using observations of intervening O VI absorption in the spectra of 7 high-redshift quasars. The observed levels of O VI absorption were somewhat lower than our initial expectations of a fairly uniform $[O/H] \sim -2.5$, and we discovered some systems with extremely low $N_{\rm O\,VI}/N_{\rm H\,I}$. We measure $N_{\rm O\,VI}/N_{\rm H\,I}$ for a sample of ~ 300 Ly-α forest lines with $N_{\rm H\,I} \geq 10^{13.5}$ cm^{-2}, including 3σ upper limits for all systems where no O VI is seen. These measurements are combined with CLOUDY-based ionization corrections to provide measurements and upper limits on [O/H] for individual Ly-α forest lines. Using survival statistics, we construct the first distribution function of observed metallicity in the Ly-α forest, finding that $\sim 60\%$ of the lines are enriched to $[O/H] \geq -3.5$. We do not find evidence for a metallicity "floor" in the IGM, as has been suggested in connection with some Population III enrichment scenarios, though the data do not rule out its existence at $[O/H] \sim -4$ or below. At $N_{\rm H\,I} \geq 10^{13.5}$ cm^{-2}, our sample probes roughly half of the baryons in the universe at $z \sim 2.5$. We estimate that $30-60\%$ of all baryons have experienced some "enrichment event" by $z \sim 2.5$ that raises their metallicity to $[O/H] \sim -2.7$.

1.1 Introduction

Observations of C IV associated with Ly-α forest lines have firmly established the existence of heavy elements in the intergalactic medium (See R.F. Carswell, these proceedings). Measurements of the IGM's metal content provide important constraints on the history of star formation and stellar recycling on cosmological scales, and are widely used as benchmarks for large cosmological simulations. The widespread belief that the IGM is enriched is based primarily on C IV observations (Ellison et al 2000), though they only probe the densest $\sim 10\%$ of the baryons in the universe, which occupy $\sim 1\%$ of the cosmic volume. In regions with gas density near the universal mean ($n_H \sim 10^{-5}$), C IV loses its sensitivity as a metallicity tracer, because most of the carbon has been further ionized to C V and higher levels.

In these environments the O VI doublet provides a much more sensitive metallicity probe, due to the high abundance of Oxygen and its ionization potential, which is well matched to the density and radiation conditions in the more tenuous IGM (Carswell et al 2002, Dave et al 1998, Burles et al 1996). The disadvantage of using O VI to measure enrichment at high redshift comes from its rest wavelength of 1032/1037Å, which causes it to be mixed in with absorption from the Ly-α forest itself. The much stronger forest lines often blanket the presence of weak O VI features or masquerade as spurious O VI lines, complicating the analysis of individual weak systems.

In these proceedings, we describe the basic results of a campaign to probe the metallicity of the IGM near the cosmic mean density at $z \sim 2.5$, using observations of O VI absorption along the lines of sight to 7 high redshift quasars. The target redshift was selected to optimize the tradeoff between sensitivity of ground based telescopes and contamination of the Ly-α forest, and we have used Monte Carlo techniques to statistically account for the effects of Ly-α forest blending. Section 1.2 describes our basic measurements, sample selection, and metallicity estimates, Section 1.3 presents our estimate of the metallicity distribution function of the IGM and in Section 1.4 we discuss the cosmological implications of the results.

1.2 Sample Selection and Metallicity Estimates

Our sample is taken from a set of 7 QSOs at $z_{em} = 2.5 - 2.8$, observed with Keck I/HIRES in 2002-2003. For each sightline, we decomposed the entire Ly-α forest into a series of Voigt profiles using R. Carswell's VPFIT software package. These fits served two purposes: first, they were used to select a parent sample of lines with $N_{\rm H\,I} \geq 10^{13.5}$ to examine for associated O VI . Then, they were used to remove the absorption signature of higher order Lyman series transitions from the data. The Ly-β and higher H I lines contribute significantly to the forest blending, and their removal increased the usable potion of the spectra by nearly 50%.

We examined the corrected spectra for O VI absorption at the redshift of each H I line in the parent sample. When O VI absorption was detected in both components of the doublet with correct relative strengths, we fit for the optimal O VI column and linewidth, b. If one or both components showed no absorption, we calculated upper limits on the O VI column density at the H I redshift. Since b is unknown for a nondetection, we found two different upper limits, one which assumes the line broadening is entirely thermal ($b_{\rm O\,VI} = b_{\rm H\,I}\sqrt{(m_{\rm H\,I}/m_{\rm O\,VI})}$), and one which assumes the broadening is dominated by bulk flows or turbulence ($b_{\rm O\,VI} = b_{\rm H\,I}$). Finally, in the common case where a possible O VI line is detected in one component of the doublet but the other component is strongly blended with Ly-α forest absorption, we fit the line and include it as a detection for completeness. This will introduce several false positive O VI identifications in the sample, and we statistically correct for this effect in the analysis below. Figure 1.2 shows the O VI and H I measurements for individual systems in the sample.

Our ultimate goal is to translate the measured H I and O VI column densities into metallicity measurements or upper limits for individual lines. However, a substantial ionization correction is required for this calculation. To estimate this correction, we have exploited the tight correlation that exists between H I column density and physical gas density in the forest (Zhang et al 1995, Schaye 2001). For each line, we invert the $N_{\rm H\,I}(n_{\rm H\,I})$ relationship in Schaye (2001) to calculate the gas number density, given the measured column density. Then, we assume an average ionizing background radiation field characteristic of quasar light which has been reprocessed by radiative transfer through the IGM (Haardt & Madau 1996). The density and spectral information is then input into the CLOUDY photoionization simulation package (Ferland et al 1998) to calculate the proper ionization correction as a function of H I column density.

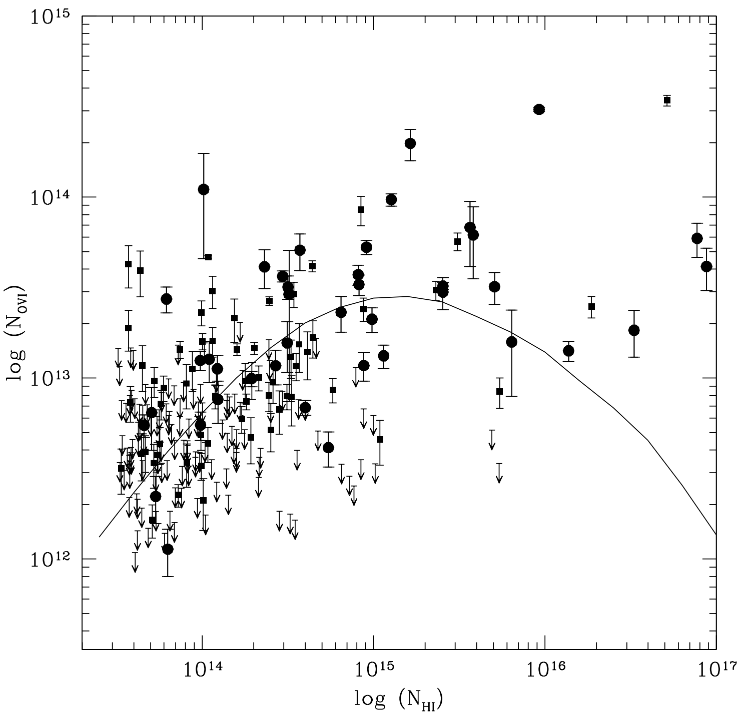

Fig. 1.1. Scatter plot of raw H I and O VI measurements for individual Ly-α forest systems. Detections are shown as large, solid circles when both components of the O VI doublet are seen, and as small solid squares when only one component of the doublet was used in the measurement. Arrows indicate 3σ upper limits where no O VI was detected. Solid curve indicates the predicted locus for a uniform enrichment of [O/H]=-2.5, using the model described in the text.

The solid line superimposed on the scatter plot in Figure 1 shows the model's predicted locus of points in the O VI -H I plane calculated for [O/H]=-2.5, a commonly quoted value for the average IGM metallicity. The data points generally scatter around the model prediction, but there are clearly a number of points, and even upper limits with column densities nearly an order of magnitude below the line. In this plane, the offset between the model and a given point is directly related to the metallicity of the line, i.e. $[O/H] = -2.5 + (N_{\text{O VI},meas} - N_{N_{\text{O VI}},model})$ for a given radiation field. We therefore see evidence of metallicities reaching $[O/H] \leq -3.5$ in the data. Figure 1.2 illustrates one example of a low metallicity system, to provide a sense of the data quality being used for the measurements.

1.3 The Metallicity Distribution of the IGM

It is not entirely clear from Figure 1.1 whether the lowest metallicity points are consistent with simple scatter about [O/H]=-2.5, or represent a distinct population of lines with statistically significant departures from the trend outlined by the model curve. To ad-

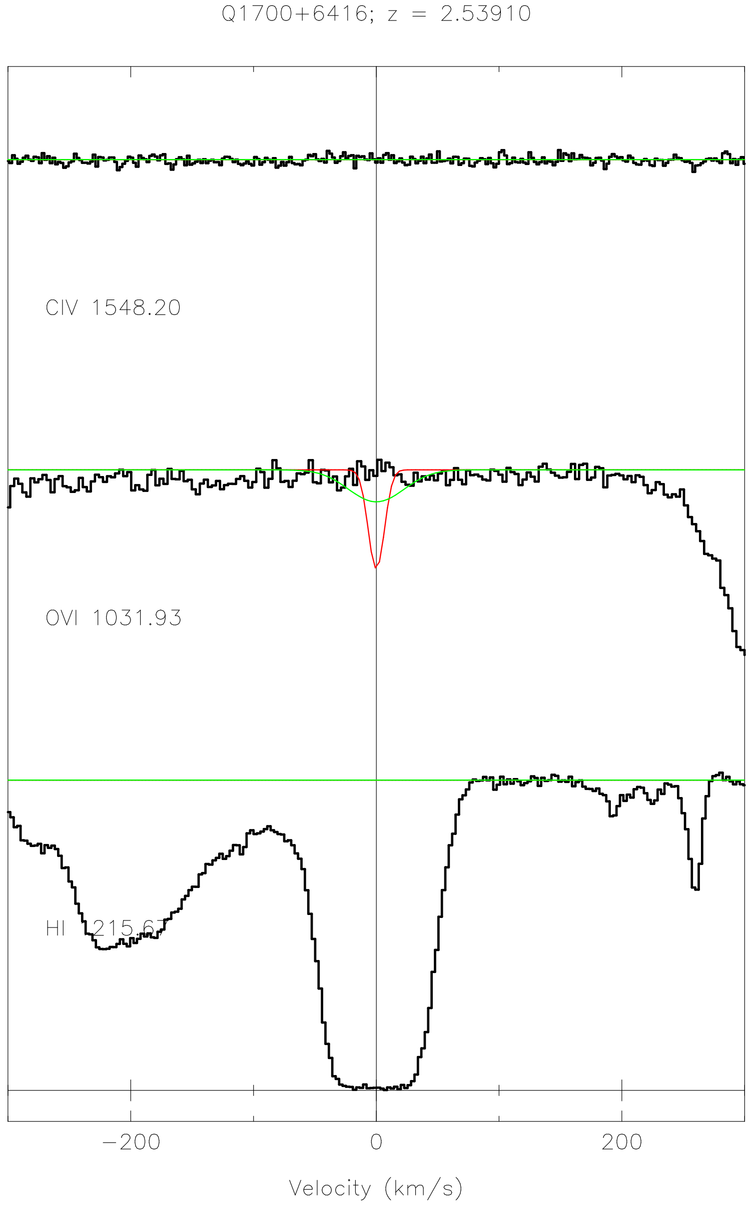

Fig. 1.2. Example of a system with very low $N_{\mathrm{O\,VI}}/N_{\mathrm{H\,I}}$. Shown are the H I profile ($N_{\mathrm{H\,I}} = 10^{14.5}$) and corresponding O VI and C IV locations. The smooth curves show the expected O VI and C IV line profiles for [O/H]=-2.5 in the case of thermal and turbulent O VI line broadening. The nondetection of O VI is inconsistent with the model; assuming our ionization spectrum is accurate, we derive a 3σ upper limit of $[O/H] \leq (-3.52, -3.04)$ for this system in the (thermal,turbulent) broadening case.

dress this question, we have used the methods of survival statistics to construct an estimate of the cumulative [O/H] distribution of the Ly-α forest.

Survival analysis differs from normal statistical methods in its more careful treatment of "censored" datasets, which contain mixtures of measurements and upper limits. We have used only the simplest survival statistic, known as the Kaplan-Meier (KM) estimator. The KM method provides a measure of the cumulative distribution of a one dimensional dataset. In our case, we measure a single number - the metallicity - for each system, along with a flag indicating whether the measurement is a detection or upper limit. To calculate the KM estimator for our data, we used the publicly available ASURV survival analysis software package (Feigelson et al 1985).

The accuracy of the KM statistic relies upon the observer's ability to accurately distinguish between detections and non-detections. This is not trivial in the O VI sample, due to the strong influence of the Ly-α forest, which both blankets true O VI lines and contaminates the sample with false positive O VI detections. In cases where both components of the doublet are detected, the identification is fairly secure, and if no line is detected in one or both of the components then the system is clearly an upper limit. However, when a line is detected in one component and the other component is blended with a Ly-α forest line, the "good" component could either be half of an O VI doublet, or an interloping H I line. In the interest of completeness, when measuring lines we included all such systems as detections. Now when constructing the KM distribution, we use Monte Carlo simulations to gauge the effect of false positive O VI IDs and statistically remove the spurious signal from the true data.

For each quasar sightline in the sample, we generated a list of simulated absorption systems using the measured $N_{\rm H\,I}$ and linewidths from the actual sample, with randomly reassigned redshifts. A metallicity was assigned at random to each line from a known probability distribution, but the individual [O/H] values were hidden from the user. The corresponding O VI column was calculated as described in Section 1.2, and the O VI and H I lines were and added back into the spectrum. Then, we measured vaues and upper limits on the "observed" O VI profiles using the same methods as in the original data. We compared the KM distribution of these measurements with the known distribution of metallicities fed into the Monte Carlo simulator. To correct for incorrect O VI IDs, we randomly demoted varying fractions of single-line-only O VI "detections" to upper limits, until the observed KM distribution of metallicities matched the Monte Carlo input distribution. For thermally broadened lines, roughly 60% of single-line detections were spurious; for turbulent broadening the contamination is somewhat higher.

Figure 1.3 shows the final, contamination corrected version of the [O/H] KM distribution function for the Ly-α forest. There are several features of note:

(1) The cumulative distribution does not reach 100%. It rather appears that $\sim 60\%$ of the forest has been enriched to $[O/H] \geq -3.5$. We have not therefore detected evidence for a metallicity "floor" in the IGM, as has been suggested in some Population III enrichment models. Such a floor may yet exist at lower metallicity, or some of the remaining 40% of the forest may be nearly chemically pristine.

(2) Only $20-30\%$ of the forest is enriched to $[O/H] = -2.5$, a commonly quoted fiducial metallicity for the IGM. The median metallicity is closer to [O/H]=-2.9. It is noteworthy that when we use only detections in the analysis (i.e. non-detections are ignored), we find results similar to prior C IV studies, i.e., that nearly all of the forest is enriched to [O/H]=-2.5.

(3) There appears to be an inflection in the cumulative distribution near [O/H]=-2.5, indicating a peak in the differential distribution at this metallicity.

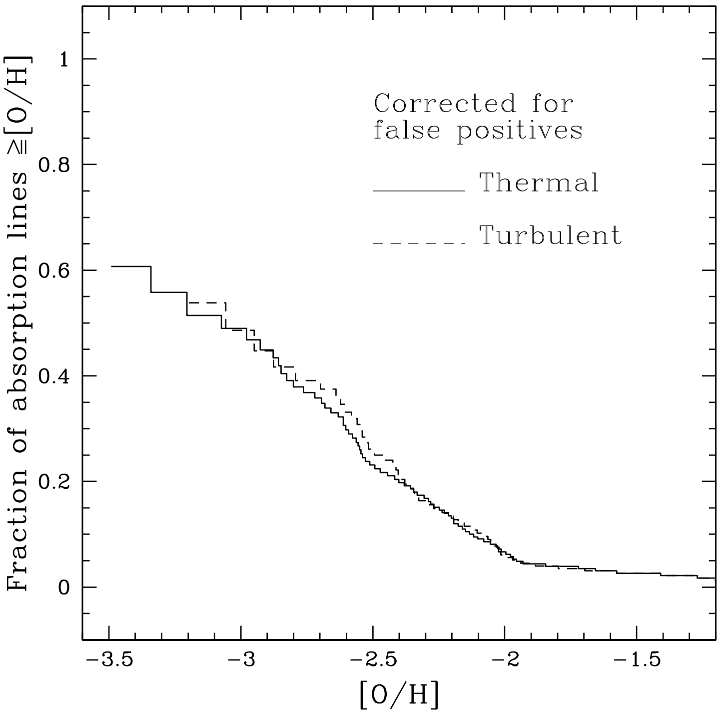

Fig. 1.3. Kaplan-Meier estimate of the cumulative metallicity distribution of Ly-α forest lines. The data have been statistically corrected to remove signal introduced by blending between O VI lines and the Ly-α forest. For the solid line, we have assumed $b_{\rm O\,VI} = b_{\rm H\,I}\sqrt{(m_{\rm H\,I}/m_{\rm O\,VI})}$ where the linewidth is not clear from the data. Dashed line is identical except that $b_{O\ vi} = b_{H\ i}$ for these cases.

Together, these results indicate that $\sim 60\%$ of the lines in the Ly-α forest contain observable levels of metals, and most of these enriched systems are clustered at $[O/H] = -2.5$, with scatter of $\sim 0.75 - 1$ dex FWHM. The remaining 40% of the lines may be enriched at $[O/H] \sim -4$ or lower.

1.4 Cosmological Implications

Having constructed a distribution function for the metallicity of the Ly-α forest, we now examine what constraints the data can place on the baryonic mass fraction and cosmic volume fraction that has been enriched by $z \sim 2.5$.

At high redshift, most of the baryons in the universe ($\geq 90\%$) reside in the distributed IGM (e.g. Rauch et al 1997). By probing to a depth of $10^{13.5}$ in H I column density, we are looking at structures with overdensities $\rho/\bar{\rho} \geq 1.2$ relative to the cosmic mean. Most of the baryonic mass in the IGM is contained in these regions slightly above the mean density, while most of the volume of the universe is at slightly below the $\rho/\bar{\rho} = 1$ (Miralda-Escudé et al 1996, Schaye 2001). For our choice of limiting H I density, we probe $\approx 54\%$ of the baryons in the universe, but still only $\approx 5\%$ of the volume.

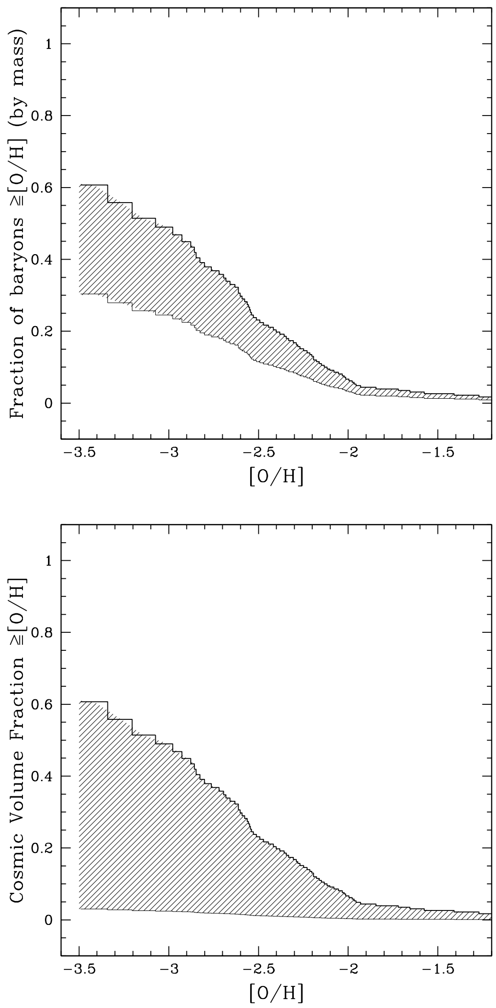

Fig. 1.4. Kaplan-Meier estimate of the cumulative metallicity distribution of Ly-α forest lines. The data have been statistically corrected to remove signal introduced by blending between O VI lines and the Ly-α forest. For the solid line, we have assumed $b_{\mathrm{O\,VI}} = b_{\mathrm{H\,I}}\sqrt{(m_{\mathrm{H\,I}}/m_{\mathrm{O\,VI}})}$ where the linewidth is not clear from the data. Dashed line is identical except that $b_{\mathrm{O\,VI}} = b_{\mathrm{H\,I}}$ for these cases.

Using these numbers, we show in figure 1.4 the fractions of mass and volume in the universe that have been enriched to various levels. The shaded regions encompass upper and lower bounds on the possible distribution, and reflect our lack of knowledge about intergalactic metallicities below the survey's limiting density. The lower bound is calculated by multiplying the KM distribution from Figure 1.3 by 0.54, since the survey probes 54% of all baryons so we directly detect this level of mass enrichment. The upper bound is derived by assuming the enrichment distribution of lines continues to arbitrarily low density, in which case the mass fraction is identical to the KM distribution. We have implicitly assumed that lower density regions of the universe are not likely to be more enriched than high density regions.

Our results imply that roughly half of all baryons have experienced some enrichment event by $z \sim 2.5$, either by passing through a galactic environment or mixing with other material that has. Whatever drove this enrichment phase (e.g. early massive stars, galactic winds) appears to have mixed a substantial fraction of the gas in the universe to an abundance of $[O/H] \sim -2.5$, but as much as half of the gas still shows $[O/H] \leq -3.5$, and may not have been affected by this particular episode of metal pollution.

The data do not tightly constrain the metal rich volume fraction of the universe. Following the same method as above, one can infer that anywhere from $5-50\%$ of the volume is enriched, depending on what happens at densities below the survey limit. We therefore suggest that future comparisons between observations and simulations should focus on enriched mass fractions rather than volume fractions, since in the foreseeable future the volume fractions will be much more dependent on untested assumptions about enrichment in cosmic voids.

1.5 Conclusions

We have used survival statistics to construct the first direct measurement of the distribution of metallicities in the Ly-α forest. These estimates were constructed using simple observations of O VI column densities, or their upper limits. Using simulations of the ionization conditions found in the forest, we translate measurements of $N_{\rm O\,VI}, N_{\rm H\,I}$ into estimates of [O/H] for each line, and construct a Kaplan-Meier estimate of the cumulative enrichment distribution of the IGM. To a limit of $[O/H] = -3.5$, we find that 60% of the lines in the forest contain metals, and within this 60% the average metallicity is approximately $[O/H] \sim -2.7$. It appears that roughly half of all the gas in the universe (by mass) has been enriched to observable levels in the first 20% of the Hubble time.

References

Burles, S. & Tytler, D. 1996, ApJ, 460, 584

Carswell, B., Schaye, J., & Kim, T. 2002, ApJ, 578, 43

Davé, R., Hellsten, U., Hernquist, L., Katz, N., & Weinberg, D. H. 1998, ApJ, 509, 661

Ellison, S. L., Songaila, A., Schaye, J., & Pettini, M. 2000, AJ, 120, 1175

Ferland, G. J., Korista, K. T., Verner, D. A., Ferguson, J. W., Kingdon, J. B., & Verner, E. M. 1998, PASP, 110, 761

Haardt, F. & Madau, P. 1996, ApJ, 461, 20

Miralda-Escudé, J., Cen, R., Ostriker, J., & Rauch, M. 1996, ApJ, 471:582

Rauch, M., Miralda-Escude, J., Sargent, W., Barlow, T., Weinberg, D., Hernquist, L., Katz, N., Cen, R. & Ostriker, J. 1997, ApJ, 489:7

Schaye, J. 2001, ApJ, 559, 507

Zhang, Y., Anninos, P., & Norman, M. L. 1995, ApJL, 453, L57+