THE DISTRIBUTION OF METALLICITY IN THE INTERGALACTIC MEDIUM AT z ~ 2.5: O \textsc{vi} AND C \textsc{iv} ABSORPTION IN THE SPECTRA OF SEVEN QSOs\(^1\)

**Robert A. Simcoe,\(^2,3\) Wallace L. Sargent,\(^2\) and Michael Rauch\(^4\)**

Received 2003 June 16; accepted 2004 January 14

**ABSTRACT**

We present a direct measurement of the metallicity distribution function for the high-redshift intergalactic medium (IGM). We determine the shape of this function using survival statistics, which incorporate both detections and nondetections of O \textsc{vi} and C \textsc{iv} absorption, associated with H \textsc{i} lines in high-resolution quasar spectra. The O \textsc{vi} sample (taken from seven QSOs at \(z_{\text{abs}} \sim 2.5\)) contains lines with \(N_{\text{O}\text{i}} \geq 10^{13.6}\) encompassing \(~50\%\) of all baryons at \(z \sim 2.5\). Our survey accounts for \(\approx 98.8\%\) of the C \textsc{iv} mass and \(\approx 90\%\) of the O \textsc{vi} mass in the universe at this epoch. We find a median intergalactic abundance of \([O/C/H] = -2.82\); the differential abundance distribution is approximately lognormal with mean \([O/C/H] \approx -2.85\) and \(\sigma = 0.75\) dex. We discuss the sensitivity of these results to the assumed form of the ionizing UV radiation field. Some \(\sim 60\%–70\%\) of lines in the Ly\(\alpha\) forest are enriched to observable levels of \([O/C/H] \geq -3.5\), while the remaining \(\sim 30\%\) of the lines have even lower abundances. Thus we have not detected a universal metallicity floor, as has been suggested for some Population III enrichment scenarios. In fact, we argue that the bulk of the intergalactic metals formed later than the first stars that are thought to have triggered reionization. We do not observe a strong trend of decreasing metallicity toward the lower density IGM, at least within regions that would be characterized as filaments in numerical simulations. However, an \([O/H]\) enhancement may be present at somewhat high densities. We estimate that roughly half of all baryons at these redshifts have been enriched to \([O/C/H] \geq -3.5\). Using a simple “closed box” model for the metallicity evolution of the IGM, we estimate the chemical yield of galaxies formed prior to \(z \sim 2.5\), finding that the typical galaxy recycled \(0.1\%–0.4\%\) of its mass back into the IGM as heavy elements in the first 3 Gyr after the big bang.

**Subject headings:** cosmology: miscellaneous — galaxies: formation — intergalactic medium — quasars: absorption lines

1. **INTRODUCTION**

Observations of C \textsc{iv} absorption in QSO spectra have unambiguously revealed the presence of heavy elements in the Ly\(\alpha\) forest at \(z = 3\) (Meyer & York 1987; Cowie et al. 1995a, 1995b; Ellison et al. 2000; Rauch, Haehnelt, & Steinmetz 1997a; Rauch et al. 1996). These results have been interpreted as evidence of widespread enrichment of the universe with the by-products of stellar nucleosynthesis, but the data at present permit the possibility of several enrichment mechanisms, from the first stars that are thought to have triggered reionization. We do not observe a strong trend of decreasing metallicity toward the lower density IGM, at least within regions that would be characterized as filaments in numerical simulations. However, an \([O/H]\) enhancement may be present at somewhat high densities. We estimate that roughly half of all baryons at these redshifts have been enriched to \([O/C/H] \geq -3.5\). Using a simple “closed box” model for the metallicity evolution of the IGM, we estimate the chemical yield of galaxies formed prior to \(z \sim 2.5\), finding that the typical galaxy recycled \(0.1\%–0.4\%\) of its mass back into the IGM as heavy elements in the first 3 Gyr after the big bang.

\(^1\) The observations were made at the W. M. Keck Observatory, which is operated as a scientific partnership between the California Institute of Technology and the University of California; it was made possible by the generous support of the W. M. Keck Foundation.

\(^2\) Palomar Observatory, California Institute of Technology, Pasadena, CA 91125; ras@astro.caltech.edu, www@astro.caltech.edu.

\(^3\) Pappalardo Fellow, Center for Space Research, Massachusetts Institute of Technology, 77 Massachusetts Avenue, 37-664B, Cambridge, MA 02139; simcoe@mit.edu.

\(^4\) Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101; mr@ociw.edu.
objects. We have limited our measurements to a single observed quantity: the column density of detected O vi and C iv lines (or 3 σ upper limit on N_{OVI}, N_{CIV} for nondetections). This paper therefore represents our best effort to describe the enrichment of the IGM using the direct, local properties of individual systems. This approach accepts a slight sacrifice in sensitivity over the statistical methods quoted above in return for a localized description of the metallicity field and a straightforward assessment of possible systematic biases. It also allows for an easy division of the total sample into subsets to study trends of metallicity with other external variants, such as H i column density or proximity to galaxies (although the latter is beyond the scope of this paper).

The literature contains several examples of intergalactic O vi searches, since it has long been known that its ionization potential and high abundance are very favorable for production in the low-density IGM (Norris, Peterson, & Hartwick 1983; Chaffee et al. 1986). The principal hurdle faced by these searches is the unfortunate rest wavelength of the O vi doublet (1032, 1037 Å). This locates the weak O vi lines deep in the Lyα forest, which smothers the signal of many real systems and further introduces a number of false positive identifications. Many of the O vi systems discovered in these surveys display large equivalent widths and rich chemical structure, as would be expected in galactic environments (Burles & Tytler 1996; Simcoe, Sargent, & Rauch 2002). Using a single spectrum of Q1422+2309, Davé et al. (1998) statistically explored the O vi content of the low-density IGM at z ∼ 3.5, finding evidence for declining abundances in lower density regions. However, Schaye et al. (2000) have claimed a detection of O vi even at very low densities, reaching below the cosmic mean. More recently Carswell, Schaye, & Kim (2002) and Bergeron et al. (2002) have discovered evidence for O vi enrichment in a number of individual systems with N_{HI} ∼ 10^{14.5} at z ∼ 2.3.

This paper expands upon these studies by using an increased number of sight lines observed at high resolution and also by incorporating the full use of nondetections in the analysis. These additional measurements have allowed us to use the methods of survival analysis to construct the distribution function of [O/H] and [C/H] in the Lyα forest. We shall demonstrate that our measured distribution function agrees quite well with very recent models produced from the completely different method of pixel statistics (Schaye et al. 2003). In § 2 we describe the observations, sample definition, and measurement methods; § 3 explains the conversion of column density measurements to abundance estimates and the application of survival statistics to estimate the [O/H] distribution; and § 4 discusses the cosmological implications of the observed metallicity distribution.

2. OBSERVATIONS

Our search targets seven bright QSOs in the redshift range 2.5 < z < 2.8, which was chosen to balance three important factors regarding the existence and observability of O vi: contamination from the Lyα forest (which worsens toward higher redshift), strength of the metagalactic UV ionizing flux (which is maximized at 2.5 < z < 3.0), and accessibility from large-aperture, ground-based telescopes (to improve the signal-to-noise ratio for the weakest lines). The sight lines are listed in Table 1, along with their QSO emission redshifts and the range of redshift covered by the absorption-line measurements. Four of the seven spectra were used in our earlier analysis of strong O vi systems (Simcoe et al. 2002), and the details of those observations are found therein. New observations of Q1217+4957, Q1347−2457, and Q1603+3820 were taken in 2002 April under variable conditions; Q1626+6433 was used in the previous paper but is omitted here because of the data’s lower signal-to-noise ratio and small redshift coverage. The observations were taken with the HIRES spectrograph on the Keck I telescope, using the UV blazed cross disperser. All exposures were taken through an 0′′86 slit fixed at the parallactic angle, for a spectral resolution of 6.6 km s$^{-1}$, and the data were reduced using T. Barlow’s MAKEE echelle reduction package.

2.1. Identification and Measurement of the O vi Systems

Because O vi is placed within the Lyα, Lyβ, and higher order Lyman forests, our first step has been to follow the procedure of Carswell et al. (2002), fitting the entire Lyα forest region to remove high-order H i transitions from the data. Beginning at the emission redshift of the quasar, each H i line in the forest was fitted with a combination of Voigt profiles using the VPFIT$^6$ software package. This procedure was extended to lower redshift until the observed wavelength of Lyα was equal to the observed wavelength of O vi at the emission redshift of the QSO. For the handful of cases in each spectrum with N_{HI} > 10^{15} (where H i lies on the flat part of the curve of growth) we performed joint fits for the H i column density using Lyα, Lyβ, Lyγ, and Lyδ. In all other cases, only Lyα was used, since the primary goal was to remove these higher order lines. As a side benefit, we obtain a full statistical description of the forest in the redshift range of the O vi survey. This information is used in § 3.7 to estimate the mass fraction of baryons probed in the sample.

| Object          | z_{em} | Δz_{OVI}^a |
|-----------------|-------|------------|
| Q1009+2956      | 2.62  | 2.295–2.553|
| Q1217+4957      | 2.70  | 2.374–2.635|
| Q1347−2457      | 2.53  | 2.329–2.525|
| Q1442+2931      | 2.63  | 2.270–2.556b|
| Q1549+1919      | 2.83  | 2.273–2.767|
| Q1603+3820      | 2.51  | 2.201–2.415c|
| Q1700+6416      | 2.72  | 2.259–2.651|

$^a$ Corrected to exclude regions within 5000 km s$^{-1}$ of the QSO emission redshift.

$^b$ The region 2.41 < z < 2.46 was excluded for this object due to the presence of a weak damped Lyα system in this wavelength range.

$^c$ The region 2.415 < z < 2.450 was excluded for this object because of the presence of a strong system that appears to be ejected from the QSO.

$^6$ Provided by R. Carswell, J. Webb, A. Cooke, & M. Irwin, available at http://www.ast.cam.ac.uk/~rfc/vpfit.html.
Once a satisfactory fit was obtained for the forest, we adjusted the original data and error arrays, using the model fit to remove the signal of Ly$\beta$ and higher order Lyman series transitions. Even small fluctuations around the continuum level were often caused by Ly$\gamma$ to Ly-7 transitions from higher redshift systems. By removing this signal the useful O vi path length in each spectrum is nearly doubled, correspondingly doubling the size of our line sample.

2.1.1. O vi Sample Selection and Measurements

For the O vi measurements, we have focused on the subset of systems with H i column densities above $N_{\text{HI}} = 10^{13.6}$ cm$^{-2}$. This represents almost an order of magnitude increase in H i depth over past C iv and O vi surveys and corresponds to clouds with overdensities of $p/p_c \sim 1.6$ relative to the cosmic mean at $z \sim 2.5$. The quality of the O vi data varies throughout the survey according to sight line and redshift, and not all regions are sufficiently sensitive to reveal O vi lines at the level expected for the weakest H i systems in the sample. However, in some regions the data quality is very high, and we shall describe below how measurements from the best regions can be combined consistently with upper limits measured in portions of the spectrum with lower signal-to-noise ratios.

We selected candidate systems using H i column densities obtained from our Voigt profile fits to the Ly$\alpha$ forest. For each line in the $N_{\text{HI}} \geq 10^{13.6}$ sample, we examined the spectrum (now free of higher order H i lines) for O vi at each sample redshift. In instances where a possible O vi line was detected at $\geq 3 \sigma$ significance, we used VPFIT to determine the column density and $b$ parameter of the O vi line. At this stage, systems were flagged as possible detections if both components of the O vi doublet were clearly visible or if absorption was present in one component but the other was strongly blended with a Ly$\alpha$ forest line. If no O vi absorption was present at the expected location of one or both doublet components, we determined 3 $\sigma$ upper limits on the O vi absorbing column. The upper limits were measured from the O vi 1032 $\AA$ transition except in cases where Ly$\alpha$ forest blending led to a cleaner result from O vi 1037 $\AA$.

When no O vi is detected, the measurement of an upper limit on $N_{\text{OVI}}$ depends upon the choice of line width, $b$, which cannot be determined from the data. Rather than guessing at the correct value to use, we have measured two upper limits for each system. For one measurement, we fix $b_{O\text{VI}}$ to the value for completely thermal line broadening in the H i--O vi gas mixture: $b_{O\text{VI}} = b_{\text{HI}}(m_{\text{HI}}/m_{\text{OVI}})^{1/2}$. The other limit corresponds to broadening from turbulent or bulk gas flows: $b_{O\text{VI}} = b_{\text{HI}}$. The actual value should lie between these two extremes. We also fix $z_{\text{OVI}} = z_{\text{HI}}$ for measuring limits on nondetections; for detections we allow the redshift to vary up to $\sim 40$ km s$^{-1}$ to optimize the fit. Often velocity differences are observed between $z_{\text{HI}}$, $z_{\text{OVI}}$, and $z_{\text{CIV}}$ in strong systems. However, for our nondetections the upper limits are not strongly sensitive to the exact placement of $z_{\text{OVI}}$, since the noise properties of the data tend to be fairly uniform over the $\sim 20$ km s$^{-1}$ velocity offsets observed between different ions. All quoted upper limits are at the 3 $\sigma$ level when no line could be fitted. In cases where VPFIT was able to fit a line with $N_{\text{OVI}} < \geq 3 \sigma$, we quote an upper limit of $N_{\text{OVI}} \leq N_{\text{OVI}} + 3 \sigma$. Regions where VPFIT found absorption at the 3 $\sigma$ level or greater are reported as detections with the best-fit column density.

In most of our systems, one component of the O vi doublet is blended with a Ly$\alpha$ forest line. If the other transition is clean of blends and shows no O vi, its interpretation as a nondetection is secure. This situation is fairly common, and we denote it as a $bd$ system, for “blend/nondetection.” But often one transition is blended with a forest line while the other shows weak absorption that could be either O vi or another interloping Ly$\alpha$ line. These systems, hereafter called the $bd$ sample (“blend-detection”), comprise a potentially serious source of false positive O vi identifications. A conservative approach is to treat all $bd$s as upper limits because of their unsure identification. However, if we assign upper limits to all $bn$s and $bd$s, we would down-weight many true detections and bias our results toward low metallicities. Yet if we were to restrict our sample to those systems where both components of the doublet are completely free of blending (accordingly, the $dd$ detections and $nn$ nondetections), the sample would be too small to provide physically interesting constraints on the metallicity of the IGM. At the measurement stage, our approach has been to treat all $bd$s and all $bd$ and $dd$ detections as detections for completeness. Later in the analysis, we use Monte Carlo simulations to estimate the degree of contamination from false positives in the $bd$ subsample and correct for their effects statistically.

2.2. Identification and Measurement of the C iv Systems

For two of the objects in the sample, we have obtained particularly high quality spectra to search for extremely weak C iv absorption features. Our intent is to compare the distribution of $[C/\text{H}]$ with that of $[O/\text{H}]$, both to check for consistency and to test the accuracy of the ionization corrections that we will use to estimate metallicities. By far the best spectrum in the sample is that of Q1549+1919, with an average signal-to-noise ratio of $\sim 350$ per resolution element throughout the C iv region. We also analyze the C iv absorption in Q1700+6416, whose spectrum has $S/N \sim 175$ per resolution element. While the second spectrum is not as sensitive for measuring the weakest C iv lines, we have included it to increase the C iv path length and improve the statistics of stronger absorbers.

As before, we use Voigt profile fits to the Ly$\alpha$ forest to determine the subset of lines to be examined for C iv absorption. However, even with such high-quality data the predicted C iv strength drops so precipitously with $N_{\text{HI}}$ that we cannot probe overdensities as low as with O vi. Therefore, we limit the C iv sample to systems with H i column densities above $N_{\text{HI}} = 10^{14.0}$ cm$^{-2}$. Because the same objects were observed for O vi, we were able to fit across the Lyman series for saturated H i lines, so the H i columns are very accurately known. At each sample redshift, we examine the location of the C iv 1548.202 $\AA$ line and measure its strength if a detection is made. If no feature is present, we determine a 3 $\sigma$ upper limit on the C iv column density for both the thermal and turbulent broadening cases. For nearly all of the systems, we used the 1548.202 $\AA$ component to measure upper limits. In the unusual case where this line was blended with a line from another redshift system, we used the 1550.774 $\AA$ component to measure the limits.

2.3. Distribution in the H i/O vi and H i/C iv Planes

We have measured O vi and H i column densities for a total of 230 Ly$\alpha$ forest lines with $N_{\text{HI}} \geq 10^{13.6}$ cm$^{-2}$ in seven sight
lines and C iv and H i column densities for a total of 83 systems with \( N_{\text{H}i} \geq 10^{14.0}\) cm\(^{-2}\) in two sight lines. These data are summarized in Figures 1 and 2, where we plot measurements or 3 \( \sigma \) upper limits for each O \( \text{vi} \) and C iv line against its H i column density. The upper limits shown in the plots are for the thermal line broadening case.

In the O \( \text{vi} \) figure, we have subdivided the detected systems according to our confidence in their identification. Filled circles denote highly probable O \( \text{vi} \), where both components of the doublet are seen in the proper ratio of strengths (the \( dd \) variety). Smaller squares are used for the \( bd \) sample, where only one of the two doublet components could be measured because of Ly\(\alpha \) forest blending with the other line. Again, we stress that this subsample contains spurious measurements from interloping H i lines—see § 3.5 we estimate that only \(~40\%\) of these points are actually O \( \text{vi} \). In false positive detections the measurements still provide upper limits on the O \( \text{vi} \) column density, so in truth some \(~60\%\) of the square points would be replaced with upper limit symbols. The C iv sample does not suffer from this sort of contamination, and all detections are weighted equally.

The solid curve in each panel indicates the locus of points predicted for Ly\(\alpha \) forest clouds enriched to \( [O/H] = [C/H] = -2.5 \) and illuminated by a slightly modified version of the Haardt & Madau (1996) ionizing background spectrum (see §§ 3.1 and 3.2 for a description of how these model predictions are generated). Our observations have reached the sensitivity required to detect metal lines at this commonly quoted abundance level for much of the sample. Even at \( N_{\text{H}i} < 10^{14.0} \), some of our O \( \text{vi} \) measurements are able to meaningfully probe the metal distribution, although the presence of several upper limits above the model curve indicates the increasing challenge at the lowest \( N_{\text{H}i} \).

Generally, the O \( \text{vi} \) and C iv data points follow the trends traced by the model predictions, with a few exceptions. At high column densities (about \( N_{\text{H}i} > 2 \times 10^{15} \)) most H i systems appear to contain O \( \text{vi} \), but the O \( \text{vi} \) is often significantly stronger than predicted. This discrepancy is not surprising and could be due to several factors. First, the recipe for producing the model curve assumes a scaling between physical gas density and H i column that may break down at higher densities where the gas becomes optically thick. More importantly, the models calculate metal strengths assuming a pure photoionization equilibrium, whereas the strongest systems may be collisionally dominated. Finally, the dense systems are likely sites of local chemical enrichment, so their metallicity could be higher by an order of magnitude or more.

At lower \( N_{\text{H}i} \), there are several systems with exceptionally low metal–to–H i ratios, both for C iv and O \( \text{vi} \). In some cases these lie almost an order of magnitude below the model prediction, even though the model should be most accurate in this regime. The presence of several such systems was initially a puzzle since we expected to find O \( \text{vi} \) and C iv absorption throughout the IGM. It is not obvious from Figures 1 and 2 whether these outlying systems are consistent with simple scatter about a trend or whether they represent a different population of lines that is statistically distinct from the rest of the sample. This question is addressed in detail below as we construct a quantitative distribution function of the intergalactic metallicity field.

### 3. ANALYSIS

Having fitted O \( \text{vi} \) and C iv line strengths for the H i–selected systems, we now translate these measurements into metallicity estimates for each line in the sample. In the following sections we describe the methods used to build the metallicity distribution using survival statistics, including corrections for false positive O \( \text{vi} \) identifications.

---

7 We use the standard notation where \([X/H]\) represents the log of the abundance for element X relative to the solar level, i.e., \([X/H] = \log (X/H)_{\odot}\).
3.1. Estimating [O/H], [C/H] for Lyα Forest Lines

Using measurements of O vi and H i, the oxygen abundance for a single system is calculated as

$$\frac{[O/H]}{[H]} = \log \left( \frac{N_{O\,vi}}{N_{H\,i}} \right) + \log \left( \frac{f_{O\,vi}}{f_{O\,i}} \right) - \log \left( \frac{N_{O}}{N_{H}} \right)_\odot,$$

(1)

where $f_{O\,vi} = n_{O\,vi}/n_0$ and $f_{H\,i} = n_{H\,i}/n_0$ are ionization fractions and we have assumed solar relative elemental abundances. Clearly the same method may be applied to calculate [C/H] from our C iv line sample. Also, the equation may be inverted to predict $N_{O\,vi}$ for different values of $N_{H\,i}$ if [O/H] is already known (this is the method used to produce the model curves in Figs. 1 and 2).

Throughout, we use the meteoritic solar abundances of Grevesse & Sauval (1998), with $A_{\text{Oxygen}} = 8.83$ and $A_{\text{Carbon}} = 8.52$ on a scale where $A_{\text{Hydrogen}} = 12$. Several revisions to these solar abundances have been suggested since the publication of Grevesse & Sauval (1998), including Allende Prieto et al. (2001, 2002), Asplund (2003), and Holweger (2001). Allende Prieto advocates a downward revision of both the carbon and the oxygen solar abundances by 0.13–0.14 dex. Likewise, Asplund reduces $A_{\text{Oxygen}}$ by 0.17 dex and $A_{\text{Carbon}}$ by 0.11 dex. Holweger uses a standard oxygen abundance that is 0.09 dex lower but a carbon abundance that is 0.07 dex higher. We have continued to use the Grevesse & Sauval (1998) abundances for ease of comparison with prior studies of intergalactic metal enrichment. Readers who prefer the Allende Prieto or Asplund values should increase all [C/H] and [O/H] ratios by 0.13–0.14 dex. Renormalization of our measurements to Holweger’s scale is slightly less straightforward. It requires a similar additive adjustment to the solar zero point, but also a hardening of the UV background field to match the relative distributions of carbon and oxygen (see § 3.6). The net effect is a downward shift in all of the metallicities listed throughout the paper, by ≈0.07–0.1 dex.

3.2. Modeling Intergalactic Ionization Conditions

The principal challenge of our metallicity calculation is an accurate estimation the ionization correction term in equation (1). We have run simulations of the ionization conditions in the IGM to calculate this term as a function of $N_{H\,i}$ column density for each line in the sample.

In the low-density Lyα forest, simulations suggest that there exists a tight correlation between physical gas density and observed $N_{H\,i}$ column density (Zhang, Anninos, & Norman 1995; Davé et al. 1999; Schaye 2001). We can use this relation to translate each $N_{H\,i}$ column density in the sample into a physical density, inverting equation (8) of Schaye (2001):

$$n_{H\,i} \approx 10^{-5} \left( \frac{N_{H\,i}}{2.3 \times 10^{13} \text{ cm}^{-2}} \right)^{2/3} T_4^{0.17} \Gamma_{12}^{-2/3} \left( \frac{f_{\gamma}}{0.16} \right)^{-1/3} \text{ cm}^{-3}.$$

(2)

The last three factors represent scaling corrections for the gas temperature, ionizing background, and fractional mass in diffuse gas and are likely to be of order unity, as argued by Schaye. This relation was derived assuming that the local collapse of Lyα forest clouds occurs nearly in hydrostatic equilibrium.

It may break down at high densities, where the gas becomes optically thick ($N_{H\,i} \gtrsim 10^{15}$), or at $\rho/\bar{\rho} \lesssim 1$, where gravitational timescales become comparable with the Hubble time. Moreover, it has not been verified observationally over most of the $N_{H\,i}$ range considered here, since Lyα forest systems typically exhibit few or no other lines that could be used to construct an estimate of $n_{H\,i}$. However, numerical investigations indicate that the scaling remains accurate from roughly the mean density to $N_{H\,i} \lesssim 10^{16}$ (Davé et al. 1999).

The intergalactic gas is highly ionized by ambient ultraviolet/X-ray radiation, whose spectrum at $z \sim 2.5$ is dominated by quasar light that is reprocessed by radiative transfer through the IGM. We have run sets of ionization calculations for several different forms of the ionizing background spectrum, which were computed as described in Haardt & Madau (1996) and kindly provided to us by F. Haardt. A range of these spectra is shown in Figure 3; details about their construction are provided in Appendix A. The curves differ both in their normalization and in their underlying UV spectral slope. The discrepancies reflect uncertainty in the exact shape of the source function in the radiative transfer equations—i.e., the average UV spectral slope intrinsic to QSOs and the relative contribution from galaxies. All of the models assume that quasar spectra in the UV are pure power laws: $F_{\nu} \propto \nu^{-\alpha}$. Intergalactic H i and He ii absorption and reemission modulate this raw spectrum, producing the features seen in the 10–1000 Å range of Figure 3. We have named the models according to their input spectral slope, so that the HM1.80 model represents a spectrum with an input $\alpha = 1.8$ power law that has been propagated through the IGM. The overall normalizations of the spectra are specified at 912 Å (1 ryd), as indicated in the plot.

Recent attempts to measure $\alpha$ by averaging quasar spectra have produced varied estimates in the range $1.5 < \alpha < 1.8$.

![Fig. 3.—Three representative models of the UV/X-ray background used in the analysis. The solid line represents our favored HM1.80 model. The ionization edges for several important transitions are labeled, with the convention that the “O vi” label marks the wavelength associated with the ionization of O v–O vi. The point with error bars represents the Scott et al. (2000) estimate of log $J_{912}$ from the proximity effect.](image-url)
The original Haardt & Madau (1996) paper used an $\alpha = 1.5$ model. Subsequently, Zheng et al. (1997) published a revised estimate of $\alpha = 1.8$, based on Faint Object Spectrograph (FOS) observations of 101 quasars. The most recent determination of the UV slope (184 QSOs; Telfer et al. 2002) revises the value again to $\alpha = 1.57$ but raises the possibility of strong variations from object to object. Each of these papers used the entire sample of FOS quasar spectra in the Hubble Space Telescope archive at the time of its publication. The samples are therefore not uniformly chosen and could be subject to selection effects. We have tested each of the different QSO models and also a HM1.80 QSO spectrum with additional $H_i$ ionizing flux from galaxies. For consistency below we adopt the HM1.80 quasar spectrum normalized to $J_{912} = -21.5$ (Fig. 3, solid line) as our fiducial X-ray/UV background. We shall show that this choice results in the best match between the intergalactic distributions of [O/H] and [C/H]. It is also roughly consistent with observations of the proximity effect and X-ray background at similar redshifts (Scott et al. 2000; Boyle et al. 1993).

Using these input spectra, we simulate the ionization balance of the IGM over a range of densities using the CLOUDY software package (Ferland et al. 1998). We treat the absorbing material as a plane-parallel gas slab, and CLOUDY calculates the ionization balance for each element, from which we extract the ionization fractions $f_{OVI}$, $f_{CIV}$, and $f_{HI}$ (Fig. 4). These are combined to calculate the second term in equation (1) along a grid of $H_i$ points. The exact ionization correction for each absorption line in the sample is then obtained by interpolating its $H_i$ column within the grid, and we combine these with the $N_{OVI}$, $N_{CIV}$, and $N_{HI}$ measurements from the data to calculate a value or $3\sigma$ upper limit for [O/H] or [C/H].

3.3. Metallicities of Individual Lines and Trends with $N_{HI}$

In Figures 5 and 6 we show the metallicity or its upper limit for each line in the $O\,VI$ and $C\,IV$ samples, plotted against $H_i$ column density. In this plot and those that follow, we have assumed the HM1.80, $J_{912} = -21.5$ fiducial spectrum for the UV background. The top panel includes all lines in each sample, and in the bottom two panels we have plotted detections and nondetections separately for viewing clarity. The dashed horizontal lines are drawn at an abundance of $[O/H] = 2.5$ to guide the eye and are not fits to the data.

Looking first at the detections, we see that over a broad range in $H_i$ density there is little change in the average metal...
abundance. At the highest densities there is a clear trend toward increasing metallicity in the O vi sample, with no corresponding change in the C iv distribution. As discussed above, this could be caused by local enrichment, but it is also likely due in part to model errors. In particular, at high densities \((N_{\text{H}1} \geq 10^{15.5})\) many of the systems will be multephase absorbers with hot collisionally ionized O vi and cooler, photoionized C iv (Simcoe et al. 2002). Thus at these densities the O vi and C iv might not be expected to follow each other too closely, and our photoionization models may break down. Nonetheless, at lower densities where the models are most accurate and where most of the lines are found, the metallicities of the detected systems are fairly uniform. To the limits of the survey \((\rho/\bar{\rho} \sim 1.6)\) we have detected no strong trend of decreasing metallicity toward the more tenuous regions of the IGM.

This statement is based only upon the detected systems; the upper limits in the bottom panel reveal a different central result: that a number of systems have metallicities significantly below the trend outlined by the detected systems. This is most easily seen in the \(10^{14.5} \leq N_{\text{H}1} \leq 10^{15.0}\) range, where our measurements can best sample the scatter both above and below the mean. In this regime most of the detected points fall near \([O/H] \sim -2.5\), but there are many nondetections whose \(3 \sigma\) upper limits are an order of magnitude lower, with little or no corresponding scatter at high metallicity (this is perhaps best seen in the top panel of Fig. 5). This pattern is likely to continue at lower densities, although we cannot test this hypothesis with the present data because of its limited signal-to-noise ratio (seen as a decrease in the sensitivity of the upper limits at low \(N_{\text{H}1}\)).

It could be that some of our lowest limits are caused by an occasional failure of the density and/or ionization model developed above. A low metallicity results when we assume that much of the oxygen is in the O vi state. If the gas is more highly ionized (e.g., through shock heating) or less ionized (e.g., if eq. [2] underestimates \(n_{\text{H}1}\)), our \([O/H]\) estimate may be erroneously low. This effect should not arise from purely intrinsic scatter about the relation in equation (2); in simulations the scatter’s amplitude is only \(\sim 0.05\) dex in \(n_{\text{H}1}\), which translates to \(\sim 0.03\) dex in \([O/H]\). However, we cannot discount the possibility of the occasional pathological case that breaks the model. By studying a large sample of lines we hope to minimize the effects of individual strange systems.

In Figure 7 we show a collection of four low-metallicity systems, to give a sense of the data quality used for our measurements. In each case, the H i profile is shown at bottom, along with the C iv 1549 Å transition and one or both components of O vi. We also show with smooth curves the predicted strength of the metal absorption features for \([O/H] = [C/H] = -2.5\) and our fiducial ionizing background spectrum. Two model curves are shown; the narrower assumes thermal line broadening and the wider assumes pure turbulence. In each of these systems C iv should be marginally detectable, and O vi would have been clearly seen. For comparison, in Figures 8 and 9 we show examples from the bd and dd samples (respectively), along with their best-fit absorption-line models.

The qualitative results of this section are not strongly sensitive to the choice of ionizing background spectrum, although there are some slight differences between the models. Harder UV backgrounds lead to a slightly lower average \([O/H]\) for the detected systems (by 0.1–0.2 dex), but there is still no positive or negative trend of metallicity with H i column density. The metallicity-density relation is affected by the strength of the soft X-ray background, in the sense that fewer X-rays (i.e., a softer overall background spectrum) would introduce a correlation of decreasing metallicity with decreasing density (see Appendix B for a more detailed discussion of this effect). The upper limits on \([O/H]\) for the lowest metallicity systems are not affected by changes in the X-ray background, but harder UV spectra can reduce these limits from \([O/H] \leq -3.15\) to \([O/H] \leq -3.4\).

In physical terms, the H i densities probed by the survey extend roughly to the boundary between the filaments and voids seen in cosmological simulations. Within the filaments, where most baryons are found, the enrichment pattern does not appear to vary with overdensity. If strong overall metallicity gradients do exist in the IGM, they must occur as the transition is made into the voids that fill most of the cosmic volume. In the moderate density regions where our O vi measurements are most sensitive, we detect significant numbers of metal-poor forest lines \(([O/H] \leq -3.2)\), and we hypothesize that analogous low-metallicity systems are likely to exist at lower densities. In the subsequent sections, we use the individual measurements and upper limits to better quantify the relative frequency of the enriched versus metal-poor systems in our sample.

3.4. Survival Analysis

To translate the measurements of individual lines into a statistical distribution of metallicity, a proper accounting must be made both of detections and of nondetections in the total sample. This problem is well suited to the methods of survival analysis, a branch of statistics that deals with “censored” data sets, which contain mixtures of measurements and upper limits.

The most general single variate survival statistic is the Kaplan-Meier product limit, which provides a nonparametric maximum likelihood estimate of a distribution directly from observed data. The Kaplan-Meier statistic and other survival methods have been discussed extensively in the astronomical literature (e.g., Feigelson & Nelson 1985; Schmitt 1985; Wardle & Knapp 1986). We follow these examples, modifying notation slightly to suit our particular application. We shall use the term “measurement” to describe the combined set of detections plus upper limits; “detection” and “upper limit” will be used when the specific context requires. We also use the notation \(Z_{\text{true}}\) to represent the actual metallicity of a line, so that for detections \(Z_{\text{true}} = Z_i\) while for upper limits its value is unknown beyond that \(Z_{\text{true}} < Z_i\).

Consider a sample of lines for which either a single variate—the metallicity \(Z\)—has been detected or an upper limit has been determined. We assume that the total set of measurements \(Z_i, i = 1, 2, 3 \ldots N\) has been sorted in order of increasing metallicity such that every \(Z_i \leq Z_{i+1}\) (where multiple measurements result in the same value, censored data points are considered smaller). We wish to use this sample to estimate the cumulative probability distribution \(P(Z \geq Z)\); the fraction of Lyα forest lines above any given metallicity threshold.

We begin at the maximum of the distribution, since for all \(Z^+ > Z_N\), every measurement in the sample is at lower metallicity; hence we estimate \(P(Z < Z^+) = 1\). According to standard convention, then

\[
P(Z > Z^+) = 1 - P(Z < Z^+) = 0.
\]
Subsequent values of $P(Z \geq Z_i)$ are constructed at each $i$ by stepping downward from the $N$th measurement using the rules of conditional probability. As the first such example, we calculate $P(Z_{\geq} Z/N)$:

$$P(Z_{\geq} Z/N) = 1 - P(Z < Z/N)$$

$$= 1 - P_{[Z < Z/N, Z < Z^+]}P(Z < Z^+)$$

$$= 1 - P_{[Z < Z/N, Z < Z^+]},$$

where $P_{[Z < Z/N, Z < Z^+]}$ denotes the conditional probability that $Z < Z/N$ given that $Z < Z^+$. It follows that $P(Z \geq Z_{N-1})$ becomes

$$P(Z_{\geq} Z_{N-1}) = 1 - P_{[Z < Z_{N-1}, Z < Z/N]}P_{[Z < Z/N, Z < Z^+]}P(Z < Z^+),$$

or for arbitrary $i$,

$$P(Z_{\geq} Z_i) = 1 - \prod_{j=i}^{N} P_{[Z < Z_j \mid Z < Z_{j+1}]}.$$  \hspace{1cm} (6)$$

The conditional probabilities are estimated by counting measurements from the ranked sample as follows. For illustration, we first assume all data points in the sample are detections (i.e., no upper limits). In this event the conditional probability at each $i$ would be

$$P_{[Z < Z_j \mid Z < Z_{j+1}]} = \frac{\text{number of detections with } Z < Z_j}{\text{number of detections with } Z < Z_{j+1}}$$

$$= \frac{n(Z < Z_j) - n(Z = Z_j)}{n(Z < Z_{j+1})} \quad \text{(no upper limits)}.$$  \hspace{1cm} (7)$$

Fig. 7.—Montage of low-metallicity nd systems. The H i Lyα transition is shown in the bottom of each panel, along with the C iv 1548 Å transition and one or both O vi transitions. The continuous curves show the predicted strength of O vi and C iv if $[O/H] = [C/H] = -2.5$. The narrow profile represents thermal broadening, and the broad profile represents turbulent broadening.
In a sample containing upper limits, the quantities \( n(Z < Z_j + 1) \) and \( n(Z = Z_j) \) are not uniquely known, since an upper limit \( Z_k \) measured at \( k \geq j + 1 \) could have a true metallicity \( Z_{k, \text{true}} < Z_j < Z_j + 1 \), or \( Z_j < Z_{k, \text{true}} \) \( \leq Z_{j+1} \), or \( Z_j < Z_{j+1} < Z_{k, \text{true}} \). In other words, an upper limit \( Z_k \) with \( k > j \) does not provide useful information about the relative weights \( n(Z < Z_j + 1) \) and \( n(Z = Z_j) \) because the relation between \( Z_{k, \text{true}} \), \( Z_j \) and \( Z_{j+1} \) is ambiguous. The Kaplan-Meier method circumvents this ambiguity by effectively ignoring upper limits with \( k > j \) in constructing \( P(Z < Z_j | Z < Z_{j+1}) \) but retaining the useful information from upper limits with \( k \leq j \). Accordingly, the conditional probability is expressed as

\[
P(Z < Z_j | Z < Z_{j+1}) = \frac{\text{number of measurements that must have } Z_{\text{true}} < Z_j}{j} \quad (8)
\]

In practice, this probability can take on one of two values, depending on whether \( Z_j \) is a detection or an upper limit. If \( Z_j \) is an upper limit, then all of the lines up to and including line \( j \) must have true metallicities less than \( Z_j \), hence \( P(Z < Z_j | Z < Z_{j+1}) = j/j = 1 \). If \( Z_j \) is a detection, then the conditional probability resembles equation (7):

\[
P(Z < Z_j | Z < Z_{j+1}) = \begin{cases} 
1 & Z_j = \text{upper limit}, \\
\frac{j - n(Z = Z_j)}{j} & Z_j = \text{detection} 
\end{cases} \quad (9)
\]

Thus the Kaplan-Meier product limit estimate of \( P(Z \geq Z_j) \), specified by equations (6) and (9), is a piecewise step function, which jumps at the \( Z \) values of detections and remains constant through upper limits.

For the Kaplan-Meier estimator to be valid, two assumptions about the distribution of upper limits must be satisfied. First, the upper limits must be independent of one another. In our case, this is clearly true when upper limits are measured for lines that are not blends of two \( \text{O~VI} \) or \( \text{C~IV} \) components. This applies to virtually the entire sample (in some cases, detections are measured in regions with blends, but never

---

**Fig. 8.** Montage of detected \( \text{bd} \) systems, shown with best-fit model curves for the detected component of \( \text{O~VI} \)
upper limits). Second, the probability that a measurement will be censored should not correlate with the measurement value itself (i.e., the censoring should be random). Our data may not strictly meet this criterion, as very high metallicity points are not likely to be censored. Yet the sample was selected based on H\textsc{i} column density—not metallicity—and since [O/H] and [C/H] do not correlate with H\textsc{i} column density (see Fig. 5), this selection method should randomize the censoring. Furthermore, since the measurements are made in data with a range of signal-to-noise ratio and blending from the Ly\alpha forest, the censoring will be further randomized by variations in the data quality. Thus, while the censoring pattern may not be random at the outset, several factors conspire to make it approximately random in the end. This can be seen in Figure 5, where upper limits are mixed in with measurements over much of the sample.

We have calculated the Kaplan-Meier distribution for our sample of metallicities using the publicly available ASURV version 1.2 software suite (Lavalley et al. 1992; Feigelson & Nelson 1985). The raw output for O\textsc{vi} is shown in Figure 10. We ran the calculations twice, once using our set of upper limit measurements that assume thermal line broadening (solid line), and once using the limits measured assuming turbulent broadening (dashed line). Both curves have included the entire \textit{dd} and \textit{bd} O\textsc{vi} samples, which will contain a (possibly large) number of false positive identifications. As expected, the curve for the turbulent sample is higher than that of the thermal sample. This is caused both by the turbulent upper limits being less sensitive than the thermal upper limits and by the introduction of more false positive identifications from statistical fluctuations in the continuum. Because of the level of contamination from false O\textsc{vi} identifications, the raw Kaplan-Meier distribution represents only an upper bound on the true metallicity distribution.

Another point of interest is that when the analysis is repeated using only detected lines (i.e., the upper limits are ignored), the median metallicity increases by a factor of \(~2\) and the enrichment pattern is similar to what has been inferred in earlier studies of intergalactic enrichment (Ellison et al. 2000; Cowie & Songaila 1998; Rauch et al. 1997a; Songaila

Fig. 9.—Montage of detected \textit{dd} systems, shown with best-fit model curves determined using VPFIT
A proper treatment of upper limits is therefore a critical component of the analysis and will have important implications for the delectability of a universal, zero-point metallicity for the IGM.

3.5. Corrections for False Positive O $\lambda$ Identifications

Using the tools developed above, we are in position to calculate correction factors that remove the effect of false positive O $\lambda$ identifications from the data. We accomplish this using Monte Carlo techniques, where pairs of H $\lambda$ and O $\lambda$ lines are generated from a predetermined distribution of [O/H] and added to the data. We then use identical measurement methods and survival analyses to test our ability to recover the input metallicity distribution.

Our philosophy has been to avoid making corrections directly to the output of the Kaplan-Meier (KM) estimation. Instead, we note that the KM distribution is constructed from a list of metallicity detections and upper limits, where an unknown fraction of the detections are actually false positives. For a given detection at risk of being a false positive (e.g., a line in the bd sample), the column density that is measured is $\rho b$ as though there existed a metallicity “floor.” A proper treatment of upper limits is therefore a critical component of the analysis and will have important implications for the delectability of a universal, zero-point metallicity for the IGM.

To produce the Monte Carlo data set, we began with the observed $N_{H\lambda}$ and $b_{H\lambda}$ measurements for each quasar sight line, but reassigned a random redshift to each absorption system. The redshifts were distributed according to recent measurements of $dN/dz(z)$ in the Ly$\alpha$ forest in our redshift range (Kim et al. 2001). For each H $\lambda$ line we then generated a corresponding O $\lambda$ doublet at the same redshift. To determine the $b_{O\lambda}$ values, we first assembled the distribution of $r_b = b_{H\lambda}/b_{O\lambda}$ for those O $\lambda$ identifications which are most secure. This ratio varies from $r_b = 1$ for the thermal broadening to $r_b = 4$ for thermal broadening, with $P(r_b) \approx 0.5 r_b$. (determined empirically from the $dd$ sample). No variation in $P(r_b)$ was observed with H $\lambda$ column density. Values of $r_b$ were drawn at random from the distribution and used to calculate $b_{O\lambda}$ for each line in the sample based upon its H $\lambda$ line width.

O $\lambda$ column densities were calculated for each line by inverting equation (1) to find $N_{O\lambda}$ given [O/H] and $N_{H\lambda}$. The ionization correction term as a function of H $\lambda$ strength was calculated with the same HM1.80 ionizing background spectrum used for the survey data (see Fig. 3). The actual metallicities for each line were drawn from an artificial, Gaussian distribution with mean $[O/H] = -2.8$ and $\sigma = 0.75$. This contrived metallicity distribution was chosen after several iterations with different backgrounds and metallicity prescriptions. We found that the correction factors did not change significantly when other reasonable backgrounds or input metallicity distributions were used. Our final background and contrived abundance distribution were chosen simply to resemble the patterns seen in the actual data.

We added the simulated set of H $\lambda$ and O $\lambda$ lines to the actual spectra for all seven quasar sight lines. This method should best replicate the actual sources of error and contamination in the real sample, including continuum fluctuations/errors, varying signal-to-noise ratio, Ly$\alpha$ forest contamination, and instrumental or other more insidious effects. To minimize the possibility of artificial lines being added where real O $\lambda$ was already present, none of the lines were placed at redshifts within 200 km s$^{-1}$ of a known line with $N_{H\lambda} \geq 10^{13.5}$. The metallicity and O $\lambda$ strength were kept hidden from the user to avoid bias in the detection process.

Finally, we searched the spectra for O $\lambda$ absorption at the redshift of each artificial H $\lambda$ line in exactly the same manner that was used for the true data. We measured O $\lambda$ column densities or upper limits for both the thermal and turbulent broadening cases at each redshift. These measurements were translated into metallicities, and a Kaplan-Meier estimate of their distribution function was constructed. These probability distributions are shown in the left panel of Figure 11. The thick solid line indicates the true metallicity distribution that was input to the Monte Carlo line generator. The solid and dashed histograms represent the measured distributions assuming thermal and turbulent line broadening, respectively.

Clearly the measured distributions systematically overestimate the input distribution, presumably either because O $\lambda$ column densities have been overestimated because of Ly$\alpha$ forest blends or because false positive interlopers have contaminated the sample. We cannot determine which particular detections are false positives, but the vast majority will be from the $bd$ sample. To bring the measured distributions in Figure 11 into agreement with the input distribution, we have demoted varying fractions $f_d$ of the $bd$ detections to upper limits and recalculated the Kaplan-Meier distribution. The specific set of points to be artificially censored was chosen.

![Uncorrected cumulative distribution function of [O/H] for the O $\lambda$ sample. Both the turbulent and thermal line broadening cases are shown. These curves represent upper bounds on the true distribution, due to contamination from false positive O $\lambda$ identifications.](image)
randomly (for several realizations), and \( f_d \) was varied until the resultant Kaplan-Meier curves produced the closest possible match to the input distribution in a least-squares sense. The exercise was repeated for both the thermal and turbulent distributions; the final corrected Monte Carlo measurements are shown in the right panel of Figure 11. Five different lines apiece are shown for the corrected thermal and turbulent distributions, corresponding to five realized combinations of the random censoring. It was not surprising to find that the false positive rate was quite high. For the thermal sample, the optimal demotion fraction was \( f_d = 57\% \), whereas for the turbulent sample \( f_d = 87\% \).

### 3.6. Final Estimates of the Metallicity Distribution

Once the \( f_d \) factors had been determined, we applied the same corrections to the actual survey data. The results are shown in Figure 12. Encouragingly, the corrected thermal and turbulent distribution functions are in quite close agreement. Comparison of Figures 10, 11, and 12 indicates that the magnitude and sense of our contamination corrections are similar for the Monte Carlo and real samples. This increases our confidence that the measurement and correction techniques are sound, at least for similar intrinsic distributions of [O/H]. As a test, we used the same correction factors to see whether we could recover a quite different artificial metallicity distribution—a step function with \( P([O/H] < -2.5) = 1 \) and \( P([O/H] > -2.5) = 0 \). Again, the Kaplan-Meier method performed well. A strong discontinuity was recovered at \( [O/H] \approx -2.45 \), although it was broadened by \( \approx 0.5 \) dex.

In Figure 13 we show the Kaplan-Meier distributions of [O/H] and [C/H] together. For this figure only, we have restricted the O vi systems to have \( N_{\text{H}_1} > 10^{14} \), for fair comparison with the C iv sample. These curves were produced assuming a HM1.80 UV background spectrum normalized to \( \log J_{912} = -21.5 \), yielding a 95% ionization of cosmic He ii at \( z \sim 2.5 \). This choice produced an excellent statistical match between the [O/H] and [C/H] curves, and it is used as our fiducial model throughout the paper. To arrive at this choice of the background spectrum, we tested a range of models with

![Image](image-url)
different spectral slopes and normalizations to determine which form produced the best least-squares match between the [O/H] and [C/H] distributions. The slopes considered included HM1.50, HM1.55, HM1.80, and a soft spectrum of HM1.80 quasar light mixed with radiation from galaxies. In the QSO+galaxy spectrum, the escape fraction of Lyman limit photons was set at 10%. The normalization of each spectrum was varied between $-21.6 \leq \log J_{\odot} \leq -21.2$.

The only spectrum besides the fiducial model that produced satisfactory results was the HM1.80+galaxy model, normalized to $\log J_{\odot} = -21.2$ (implying 93% ionization of He ii). In this scenario the [O/H] and [C/H] distributions were both shifted to the left of those in Figure 13, by $\sim 0.25$ dex. The lower metallicities can be attributed to extra H i ionizing photons supplied by the stars. These boost the hydrogen ionization correction but do not strongly affect the metal lines, which are governed by harder UV radiation that can only be supplied by quasars.

In choosing the background spectrum to match [O/H] with [C/H], we have implicitly assumed that [C/O] = 0 in the low-density IGM and that the Grevesse & Sauval (1998) solar abundances are accurate. As discussed in § 3.1, several changes have been suggested for the solar abundances in recent years. Substitution of the Allende Prieto et al. (2002) or Asplund (2003) carbon and oxygen values should not affect our choice of UV background, since the zero points for these elements were revised by similar amounts. However, on the Holweger (2001) scale, the solar (C/O) ratio is increased by 0.16 dex. Moreover, observations of metal-poor galactic halo stars indicate that [C/O] $\sim -0.5$ may be a more appropriate benchmark for low-metallicity environments like the Ly$\alpha$ forest clouds (Akerman et al. 2004).

To gauge the importance of these effects, we used our full suite of UV background models to compare the distributions of [O/H] versus [C/H] + 0.5 (for the metal-poor star scenario) and [O/H] + 0.09 versus [C/H] − 0.07 (to mimic Holweger’s solar abundances). Generally, we found that harder UV backgrounds resulted in higher [C/O] ratios. Accordingly, the Holweger abundances favored a HM1.55 background but ultimately yielded similar intrinsic [O/H] and [C/H] distributions as our fiducial model. For all normalizations, the matches between the Holweger curves were statistically inferior to those of our fiducial model.

For the [C/O] = −0.5 case, a very soft background spectrum was needed to suppress the measured carbon metallicities relative to oxygen. In fact, the HM1.80+galaxy spectrum was the only viable model for any choice of solar abundances. Normalizations in the range $-21.6 \leq \log J_{\odot} \leq -21.4$ all produced superb matches between the distributions of [O/H] and [C/H] + 0.5. Thus, to produce an intergalactic [C/O] ratio resembling that of metal-poor halo stars, a soft UV background spectrum is required. In this scenario, the median carbon abundance is reduced to [C/H] = −3.1 and the median oxygen abundance remains near [O/H] = −2.7.

Figure 12 (which includes all O vi lines) represents our best estimate of the metallicity distribution function of the Ly$\alpha$ forest, using our fiducial choice of background spectrum. Even at the lowest observed values, the cumulative distribution does not reach 100%. Roughly 70% of the forest has been enriched to [O/H] $\geq -3.5$. Thus we have detected neither a metallicity “floor” in the IGM nor an abrupt transition toward chemically pristine gas at low densities. An abundance floor could exist at [O/H] $\leq -3.5$, or some of the remaining 30% of lines may be nearly metal-free.

For our fiducial ionizing background model, we find a median intergalactic abundance of [C/O, [O/H] = −2.81, quite similar to prior studies suggesting $-2.5 \leq [O/H] \leq -2.0$ (Cowie & Songaila 1998; Ellison et al. 2000), although a factor of 2−4 lower. The mean is formally unconstrained, as our lowest measurements are upper limits. Some further insight may be gained by examining the differential abundance distribution, which we have also calculated using ASURV using the algorithms presented in Wardle & Knapp (1986). The differential O vi distribution is shown in Figure 14 and is quite similar to the C iv distribution which is not shown. The vertical dotted line indicates the weakest detection in the sample (although there are some lower upper limits). The lines appear to be drawn from a single, fairly uniform distribution in [O/H] that peaks near the median metallicity. We cannot probe the lower half of the distribution as it lies below our sensitivity threshold, but we know that there must be a substantial drop-off—since we have already accounted for $\sim 70\%$ of the lines, the integrated area to the left of the sample cutoff can be at most $\sim 30\%$. The observed part of the distribution resembles a unity normalized Gaussian probability density function, with mean ⟨[C/O]⟩ = −2.85 and $\sigma = 0.75$ dex. In terms of $Z/Z_{\odot}$, the distribution of metallicity would be lognormal.

To illustrate how our model corresponds to what is seen in the actual spectra, we show again in Figure 15 the raw Kaplan-Meier O vi distribution, which has not been corrected for false positive identifications. Both the thermal and turbulence-broadened measurements are shown, as the thick dotted and solid lines, respectively. On the same graph, we have plotted the raw Kaplan-Meier distributions of a simulated data set with the lognormal metallicity distribution described above (shown as matching thin curves). A simple, single population model for the metallicity distribution (along with a uniform ionizing background) reproduces the actual
survey results extremely well, over the entire measurable range.

3.7. Statistical Tests for Correlation between \( N_{\text{HI}} \) and \([\text{O/H}]\)

The concepts of survival analysis can also be extended to treat bivariate data. This allows us to quantify the trend of \([\text{O/H}]\) with \( N_{\text{HI}} \), even though the distribution of \([\text{O/H}]\) is censored.

Several tests have been devised to rate the significance of correlations in censored data sets, including the Cox proportional hazard method, the generalized Kendall’s \( \tau \) statistic, and generalized Spearman’s \( \rho \). These tests are implemented in ASURV along with a number of techniques for linear regression of censored bivariate data. We have run our measurements through each of the correlation tests and performed a Buckley-James regression to determine the slope of any correlations between \([\text{O/H}]\) and \( N_{\text{HI}} \). We used the three different prescriptions for the ionizing background that produced plausible results in the previous section: our “fiducial” HM1.80 quasar spectrum, the HM1.80+galaxy spectrum normalized to \( \log J_{912} = -21.2 \) (which produces \([\text{C/O}] = 0\) but with lower overall metallicities), and the HM1.80+galaxy spectrum normalized to \( \log J_{912} = -21.5 \) (required if \([\text{C/O}] = -0.5\)).

The results are illustrated in Figure 16. To produce the data points shown in this plot, we have divided the sample into bins of \( N_{\text{HI}} \) and used the Kaplan-Meier statistic to determine the median \([\text{O/H}]\) and its interquartile range for each bin. The medians are shown as filled circles, and the quartiles are shown as terminated vertical bars. For some bins, our measurements were not sensitive enough to reach the 75th (lowest metallicity) percentile; these bins are indicated with arrows. When the distribution function does not even reach the median for a bin, its lowest reliable value (typically around the 40th percentile) is indicated with a horizontal dash. For each plot, we also show the best-fit relation between \( N_{\text{HI}} \) and \([\text{O/H}]\), determined using Buckley-James regression over the range \( 10^{13.6} \leq N_{\text{HI}} \leq 10^{15} \). Despite the figure’s appearance, the line fit is not found through \( \chi^2 \) minimization of the binned data.
Its solution more closely resembles a maximum likelihood fit to the unbinned points and upper limits.

From the binned data, it is clear that with the \( N_{\text{H}} \geq 10^{15} \) systems included, a significant correlation is present for any choice of UV background. This is confirmed by the statistical tests and regression. However, we have argued that our metallicities in this range are less reliable. Above \( N_{\text{H}} = 2 \times 10^{15} \), a large fraction of systems no longer conform to our simple, quiescent, photoionized model of the Ly\( \alpha \) forest. In Simcoe et al. (2002) we described how these absorbers contain mixtures of hot, probably collisionally ionized O \( \text{vi} \), together with cooler photoionized C \( \text{iv} \) and lower ionization species. They may be the remnants of galactic winds or shocked parcels of unusually metal-rich gas in assembling halos or larger structures. These environments require a more sophisticated physical model than our simple density and photoionization scalings. Accordingly, we focus on systems with lower densities for our regressions.

In the range below \( N_{\text{H}} = 10^{15} \), there is no obvious signature of a metallicity gradient in the medians and quartiles, and in fact our regression fits yielded zero slope for two of our three plausible background models. For the fiducial UV background model (Fig. 16, top), we found a 50%–75% probability that no correlation existed using the Cox method and Kendall’s \( \tau \). Spearman’s \( \rho \) yielded a 88% probability of no correlation. The slope of the regression line was \( d[O/H]/d \log N_{\text{H}} = 0.05 \pm 0.13 \), statistically consistent with zero. The HM1.80+galaxy model normalized to \( J_{012} = -21.2 \) yielded similar results, although in this case, the best-fit metallicity decreased mildly with increasing \( N_{\text{H}} \) (with slope \( -0.07 \pm 0.13 \)). This represents a physically unlikely scenario. There is evidence of a metallicity-density correlation at the \( \sim 2.3 \sigma \) level if we use our softest background, the HM1.80 + galaxies with \( J_{012} = -21.5 \) (the [C/O] = –0.5 condition). For this UV background the various statistical tests give a correlation probability between 85%–95%, with \( d[O/H]/d \log N_{\text{H}} = 0.334 \pm 0.14 \).

These statistical tests support the qualitative assertion of § 3.3: at low densities our data do not show compelling evidence of a gradient in the intergalactic metallicity, although for our softest model of the ionizing spectrum there is some indication of a trend. Above \( N_{\text{H}} \geq 10^{15} \) (\( \rho/\bar{\rho} \sim 11 \)) there is a clear rise in the median [O/H], which may mean that a boundary has been crossed into environments with strong local enrichment. A corresponding jump is not seen in [C/H], perhaps indicating that the stronger absorbers are physically more complex or multiphased. In the quiescent, rarefied IGM, the average abundance remains roughly constant with density to the limits of our survey (\( \rho/\bar{\rho} \sim 1.6 \)). At the very least we have not detected a dramatic boundary below which the IGM is chemically pristine.

### 3.8. Comparison with Recent Results from Pixel Statistics

A recently published study of C \( \text{iv} \) by Schaye et al. (2003, hereafter S03) compares observed pixel statistics with numerically simulated spectra to determine the median intergalactic carbon abundance and trend of [C/H] with overdensity. Our results are consistent with those of S03 where the two studies can be compared, and the agreement is particularly good regarding the shape of the metallicity distribution function. S03 emphasize the presence of a metallicity-density correlation; in our interpretation of the data presented above, plausible models of the UV background can lead to positive, negative, or null correlation results, so we do not claim to see such compelling evidence of a gradient.

S03 favor an ionizing spectrum similar to our HM1.80+ galaxies prescription, normalized to \( J_{012} = -21.5 \) (at \( z \sim 2.5 \)). This is the form we used to produce [C/O] = –0.5 in the IGM, so although S03 do not discuss oxygen abundances, we expect that their [O/H] distribution would be higher than the corresponding [C/H]. Using this model we found a median carbon abundance of [C/H] = –3.1 and a median oxygen abundance of [O/H] = –2.7. In S03, the median carbon abundance increases from [C/H] = –3.84 to –3.19 over the range \( 10^{15} \leq N_{\text{H}} \leq 10^{16} \), with \( d[O/H]/d \log N_{\text{H}} = 0.43^{+0.07}_{-0.09} \) (note a factor of \( 3^\frac{1}{2} \) conversion from \( d[O/H]/d \log N_{\text{H}} \) to \( d[O/H]/d \log N_{\text{H}} \), see eq. [2]). Our measurements are slightly higher than S03’s over this entire range, although they are comparable near \( N_{\text{H}} \sim 10^{15} \). Our slope for the [O/H] versus \( N_{\text{H}} \) fit using this background is somewhat lower than S03’s (0.33 vs. 0.43), but still within the 1 \( \sigma \) errors. Both we and S03 find lower [C/H] values than earlier studies (e.g., Songaila & Cowie 1996; Ellison et al. 2000), but this difference is primarily due to our use of a softer spectrum for the UV background.

S03 have also tested their calculations using a background spectrum similar to our fiducial model (their “Q” spectrum). For this case, they find a higher median [C/H] = ~2.8 to ~2.9 and little or no correlation between metallicity and density, in good agreement with our results. Moreover, both methods derive a lognormal distribution of metallicities with \( \sigma \approx 0.75 \) dex.

For the regression analysis, we have taken a slightly different approach from S03 by dividing our sample at \( N_{\text{H}} = 10^{15} \), reflecting our misgivings about the ionization modeling of the stronger systems. S03 do not split their C \( \text{iv} \) sample along these lines, although J. Schaye (2003, private communication) has indicated that their results do not change substantially if the domain is likewise restricted. Interestingly, if we perform a [C/H] regression using the HM1.80+galaxy UV background with \( J_{012} = -21.5 \) and all of our C \( \text{iv} \) systems at all densities, we obtain a slope very similar to that of S03: \( d[O/H]/d \log N_{\text{H}} \approx 0.412 \pm 0.12 \), although the overall normalization of our [C/H] curve is higher by 0.26 dex. The errors on our [C/H] regression become extremely large if we consider only systems with \( N_{\text{H}} < 10^{15} \), so it is difficult to compare our C \( \text{iv} \) results in this regime. We showed above that our [O/H] regression for this UV background and density range produced a mild metallicity-density correlation. However, a fit for [O/H] including systems with all H \( \text{i} \) column densities produces a much steeper slope than S03, discrepant at the 3 \( \sigma \) level.

In the end, interpretations of a metallicity gradient are tied to assumptions about the shape of the UV/X-ray background (see Appendix B) and the range of \( N_{\text{H}} \) appropriate to the regression analysis. We have found three versions of the background spectrum that produce plausible relative distributions of [C/H] and [O/H]; for two of these there is no slope in the metallicity distribution, and for our third, softest model we see a mild slope. Where they can be compared, these results are fairly consistent with those of S03, who also find little or no slope for QSO-dominated backgrounds, but a metallicity gradient for QSO+galaxy backgrounds. In no case do we observe a dramatic decline in the metallicity that would indicate a chemical enrichment boundary in the IGM. For all models, the [O/H] slope is much steeper if we include high column density systems, but in these cases the slope becomes too severe to
be consistent with our low-density result, our [C/H] fit, or the [C/H] fit of S03. We interpret this as the onset of a more complicated ionization structure in the high-density systems.

3.9. Cosmic Mass/Volume Fractions Probed by the Survey

We now present a simple method for recasting the observed fractions of absorption lines at different abundances into more physical terms. We are particularly interested in the mass and volume fractions of the universe that are enriched to various levels. To estimate this distribution, we first recall that we have fitted Voigt profiles to every H i line in the Lyα forest. This was originally done to remove higher order H i transitions for the O vi search, but the line lists also provide detailed information on the column density distribution of H i in the exact redshift window of the survey. This information may be used to calculate the total mass fraction of baryons probed by the survey and, by extension, the volume fraction.

Our mass fraction calculation follows the development of Schaye (2001), and we begin with his equation (16):

$$\Omega_g \propto \int N_{H1}^{1/3}f_{(N_{H1}, z)}dN_{H1}. \quad (10)$$

Here $f_{(N_{H1}, z)} = d^2N/dN_{H1}dX$ represents the number of H i absorption lines per unit $N_{H1}$ and per unit absorption path length and is calculated directly from the H i line lists. We have assumed (as in Schaye) that the gas is isothermal and that the fraction of the total cosmic mass contained in gas is close to $\Omega_b/\Omega_m$. Using equation (10), we can infer the fraction of $\Omega_g$ contained in each decade of $N_{H1}$:

$$\frac{d\Omega_g}{d \log N_{H1}} = \frac{d\Omega_g}{dN_{H1}}N_{H1}^{4/3}f_{(N_{H1}, z)} \quad (11)$$

This quantity is plotted in Figure 17, with the points and errors taken directly from the H i distribution of the data. The vertical normalization of the plot is arbitrary, and the points are equally spaced in $\log N_{H1}$. The distribution should be quite accurate over the range $10^{12.5} < N_{H1} < 10^{15}$, where distinct absorption lines are clearly visible in the data and line saturation is not severe. At higher $N_{H1}$, there is an increased uncertainty in our column density measurements for some systems. Since the primary purpose of the line fits was to facilitate the O vi search, the fit quality was not as uniformly high over all H i transitions for high-density systems that did not have bearing on an O vi measurement. Furthermore, the exact shape of the turnover below $N_{H1} \sim 10^{11}$ is the subject of some contention, as it results from a combination of real, physical effects and observational incompleteness. Although we may miss some amount of the mass in this region, cosmological simulations indicate that there should be a real and significant drop in the mass density contained in systems below $N_{H1} \sim 10^{10.5}$. Whatever the case, the accuracy of the data is highest over the range that contains most of the mass. We shall show below that these uncertainties do not change our qualitative results.

The H i cutoff of the O vi sample ($N_{H1} \geq 10^{13.6}$) is shown in Figure 17 as a dashed line. We wish to determine what fraction of the total gas mass lies to the right of this line. A simple inspection suggests that this fraction is close to one half, which turns out to be remarkably close to the true value. Since the data are equally spaced in the log, we may simply sum the points to the right of the line and normalize by the sum of all points to determine what fraction of $\Omega_g$ is probed by the survey. Depending on whether lines with $N_{H1} > 10^{17.5}$ are included in the calculation (since they suffer from small number statistics), we find that the survey probes between 51%–57% of the total $\Omega_g$. Incompleteness at $N_{H1} < 10^{12}$ has little effect on the results, although incompleteness at $10^{12} \lesssim N_{H1} \lesssim 10^{12.5}$ could reduce our coverage to ~42% of $\Omega_g$ if we had undercounted these lines by a factor of 3 (a fairly conservative estimate). Accounting for a range of uncertainty in our measurement of the H i column density distribution, we estimate that our survey probes roughly 42%–57% of the gas in the universe at $z \sim 2.5$ by mass, with the most likely value being close to 50%.

In Figure 18 we apply this information to determine the mass fraction of baryons that have been enriched to a given oxygen abundance, which we call the enriched mass function, or EMF. The two curves that bound the shaded region of the plot represent upper and lower limits on the EMF, derived using two different assumptions about the trend of [O/H] versus $N_{H1}$ below our survey’s H i threshold. If we define $P([O/H]; N_{H1})$ as the differential probability that a line with $N_{H1}$ will possess an oxygen abundance [O/H], the EMF is defined as

$$\text{EMF} = \int_{[O/H]}^{\infty} P([O/H]; N_{H1})dN_{H1}d([O/H])$$

To produce the upper bound, we suppose that the intergalactic enrichment pattern seen in our data continues to arbitrarily
Low densities, filling the entire volume of the universe. In this case, \( P_{(O/H; N_{H1})} \) is independent of \( N_{H1} \) (See Fig. 5) and the integrals over \( \log N_{H1} \) and \( [O/H] \) may be separated. The ratio of the density integrals reduces to unity, and we are left with the expression

\[
 f_{\text{mass}}(\geq [O/H]) \leq \int_{[O/H]}^{\infty} P_{(O/H; N_{H1})} d\left(\frac{[O/H]}{[H]}\right) = P_{(\geq [O/H])}. \tag{13}
\]

Thus the upper bound for the EMF is simply the cumulative distribution of line enrichment, i.e., the Kaplan-Meier distribution shown in Figure 12. We have implicitly assumed that the lowest density regions of the IGM are not more heavily enriched than the highly overdense areas.

To produce the EMF’s lower bound, we suppose that all gas in clouds with \( N_{H1} < 10^{13.6} \) is chemically pristine, i.e., that we have already observed all of the heavy elements in the universe. Now, equation (12) becomes

\[
 f_{\text{mass}}(\leq [O/H]) \geq P_{([O/H])} \times \int_{[O/H]}^{\infty} d\Omega / d [O/H] \frac{dN_{H1}}{d \log N_{H1}} d(\log N_{H1}) \approx 0.5 P_{([O/H])}. \tag{14}
\]

In the last step, we have used the above estimate that ~50% of all baryonic mass is in clouds with \( N_{H1} \geq 10^{13.6} \). The upper and lower bounds on the EMF given by equations (13) and (14) were used to produce the shaded regions in Figure 18.

It is more difficult to estimate the volume filling factor of enriched gas without reference to simulations, because of the complex nature of the Ly\( \alpha \) forest topology and the lack of a simple analytic form for the volume fraction \( dV/dN_{H1} \). However, simulations can easily calculate the volume fraction within a given H\, I density contour, or which contains a certain fraction of \( \Omega_b \). Figure 20b in Miralda-Escude et al. (1996) may be used to estimate the filling factor of the contour containing half of the baryons at \( z = 3 \). This number turns out to be small, only ~5% of the total volume of the universe. One can guess why this is the case from Figure 17; we probe to an overdensity of \( \rho / \bar{\rho} \approx 1.6 \), and most of the mass in the universe is at densities slightly above the mean (the filaments), while most of the volume is at densities slightly below the mean (the voids). We again emphasize, at the lowest densities where it is possible to probe the intergalactic metallicity, we only trace cosmic filaments—we have not reached the voids.

3.10. Contribution of Intergalactic Oxygen and Carbon to Closure Density

We have estimated the quantity \( \Omega_{C_{IV}} \) using two different methods, initially to compare with previous studies and then to test the consistency of our ionization model. The first calculation takes a direct sum of the observed C\, IV column densities, as in Songaila (2001):

\[
 \Omega_{C_{IV}} = \frac{1}{\rho_c} m_{C_{IV}} \sum \frac{N_{C_{IV,i}}}{c/I_0} \Delta X_i. \tag{15}
\]

Here \( \rho_c = 1.89 \times 10^{29} \text{ g cm}^{-3} \) is the current closure density, \( m_{C_{IV}} \) is the mass of the C\, IV ion, and the upper sum includes all observed C\, IV lines. The lower sum represents the total absorption path length of the sample (defined in the previous section; note that our formula for \( \Delta X \) differs from Songaila’s), which summed over our two C\, IV sight lines comes to \( \Delta X = 3.27 \). Applying this to the data we find \( \Omega_{C_{IV}} = 3.50 \times 10^{-3} \text{ h}^{-1} \) (where \( H_0 = 100 \text{ h km s}^{-1} \text{ Mpc}^{-1} \)). This is in excellent agreement with other estimates of \( \Omega_{C_{IV}} \) at \( z \sim 2.5 \) from the literature (Songaila 2001; Boksenberg et al. 2003). At least for \( z \geq 4 \), this may indicate that the C\, IV systems are enriched and/or ionized by local sources (Pettini et al. 2003; Boksenberg et al. 2003).

With a benchmark in hand, we now recalculate \( \Omega_{C_{IV}} \), this time starting from the observed distribution of H\, I in the forest and applying our metallicity and ionization models to predict the total amount of C\, IV. A comparison of this result with the straightforward sum from equation (15) tests the consistency of the enrichment model. We begin with the H\, I column density distribution function \( f_{(N_{H1}, z)} \), calculated from our H\, I line fits as described in the previous section. We may perform a weighted integral of \( f_{(N_{H1}, z)} \) to obtain an analog of the last expression in equation (15), with H\, I substituted for C\, IV:

\[
 \frac{\sum N_{H1}}{c/I_0} \Delta X \approx \left( \frac{c}{H_0} \right)^{-1} \int N_{H1} f_{(N_{H1}, z)} dN_{H1}. \tag{16}
\]

Folding in metallicity and ionization corrections, we derive the C\, IV mass density, again through analogy with equation (15):

\[
 \Omega_{C_{IV}} = \frac{1}{\rho_c} m_{C_{IV}} \times \left[ \frac{C}{H} \right] \left( \frac{10^{13.6}}{c/I_0} \right)^{-1} \int N_{H1} f_{(X_{\text{Hi}}, z)} \frac{f_{C_{IV}}}{f_{H1}} dN_{H1}. \tag{17}
\]
The ionization correction factors, taken from our CLOUDY calculations (and shown in Fig. 4), are density-dependent and shown in Table 2. This also suggests that a major portion of the C iv and O vi mass in the universe has been detected in the survey. This is achieved by changing the limits of the H i integration to match our column density cutoffs—$N_{\text{HI}} \geq 10^{13.6}$ for O vi and $N_{\text{HI}} \geq 10^{14.0}$ for C iv. According to this method, our limits probe 98.8% of the C iv mass and 90% of the O vi mass.

### 4. DISCUSSION

We have shown that cosmological filaments are enriched with oxygen and carbon to near the mean gas density in the universe and that the median $[C/\text{O}] = -2.82$ is similar to previous estimates, although about a factor of 2 lower. We have also shown several systems with very low abundances, implying that ~30% of Ly$\alpha$ forest lines have metallicities of $[C/\text{O}] \leq -3.5$. In this section we examine our results in the context of cosmic chemical evolution models, to assess their relevance for distinguishing between different enrichment mechanisms.

In Figure 19 we show a variant of the metallicity-density relation from the O vi sample, now recast in terms typically used in numerical simulations. Points from the dd sample are shown with large symbols; the bd systems are shown with small dots, ~60% of which are false positives. The error bars on detected points have been omitted for clarity. Along with the data points, we have indicated the expected metallicity-density relations for different chemical enrichment scenarios. We consider two classes of models: one where metals are expelled at very early times by the first generation of stars and one where the ejection epoch occurs much later and is associated with bursts of ”normal” star formation and galactic winds.

Recent studies of star formation in zero-metallicity environments show that the first stars in the universe probably formed via H$_2$ cooling (Abel, Bryan, & Norman 2002; Bromm, Coppi, & Larson 2002; Ostriker & Gnedin 1996). These ”Population III” stars were uniformly massive ($M \sim 150-250 \ M_\odot$) and short-lived, culminating in pair-instability supernovae that disrupted the entire mass of the star, leaving no remnant (Heger & Woosley 2002). Yield calculations by these authors indicate that fully half of the total stellar mass can be converted into metals and expelled. All of this takes place prior to $z \sim 30$, at which point the stars are in comparatively small halos that are close together. Thus the Population III objects provide a potentially efficient mechanism to enrich a large fraction of the cosmic volume. However, this mode of star formation is also self-regulating, which leads to a natural limit to the quantity of metals that can be produced. When the first Population III objects form, they shine brightly in the near ultraviolet and emit enough photons in the Lyman Werner

### TABLE 2

**Metal Density in the Universe**

| Quantity | $\Omega_{\text{C IV}}$ ($\rho/\rho^*$) Method |
|----------|------------------------------------------|
| $\Omega_{\text{C IV}}$ | $3.50 \times 10^{-8}$ eq. (15) $^a$ |
| $\Omega_{\text{C IV}}$ | $1.31 \times 10^{-8}$ eq. (15) $^a$ |
| $\Omega_{\text{C IV}}$ | $1.78 \times 10^{-8}$ eq. (17) |
| $\Omega_{\text{C IV}}$ | $7.89 \times 10^{-8}$ eq. (17) |
| $\Omega_{\text{carbon}}$ | $5.10 \times 10^{-7}$ eq. (17)$^b$ |
| $\Omega_{\text{oxygen}}$ | $1.38 \times 10^{-6}$ eq. (17)$^b$ |

$^a$ The first row was calculated using the entire C IV sample; the second omits the three strongest lines (out of 83), which contain over half of the mass and may not be representative of the intergalactic distribution (see text).

$^b$ Calculated using eq. (17), but with the ionization correction factors $f_{\text{C IV}}$ or $f_{\text{O VI}}$ omitted.

Using these values in equation (17), we find $\Omega_{\text{C IV}} = 1.78 \times 10^{-8} h^{-1}$, similar to the value found from equation (15), but about a factor of 2 lower. This discrepancy is less significant than it may first appear, since the sum in equation (15) is always dominated by the few strongest systems in the sample. In our case, three strong outliers from a sample of 83 lines contain over half of the total C IV column density. These are clearly seen in Figure 2; they are found within very strong C IV systems that probably do not represent tenuous intergalactic matter. A reevaluation of equation (15) without these three lines included yields $\Omega_{\text{C IV}} = 1.31 \times 10^{-8}$, bringing the estimates from both methods into close agreement (see Table 2). This also suggests that a major portion of the C IV mass in the universe may be contained in a small number of systems that are highly enriched or harbor unusual ionization conditions.

When estimating $\Omega_{\text{O VI}}$, it is considerably more difficult to perform the calculation in equation (15) because of Ly$\alpha$ forest blending and false positive identifications. We have accounted for these effects in our determination of the metallicity distribution, so it is much more straightforward to apply equation (17), yielding $\Omega_{\text{O VI}} = 7.89 \times 10^{-8}$. By omitting the O vi or C iv ionization corrections from equation (17) (but retaining the H i correction) we may estimate the total contribution of carbon or oxygen in all ionization states to the closure density. The resulting values are listed in Table 3 along with the values for the C iv and O vi ionization states. Qian, Sargent, & Wasserburg (2002) have constructed an observationally motivated enrichment model for the galactic halo, requiring several generations of supernovae from very massive stars. Their prediction for $\Omega_{\text{C IV}}$ from this model is an order of magnitude lower than the estimate presented here, and their $\Omega_{\text{O VI}}$ is 1.65 times larger than our measurement. We caution the reader that estimates of $[\text{C/O}]$ from our measurements will not be meaningful, as we have constrained our models of the ionizing background using assumptions about the $[\text{C/O}]$ ratio.

Equation (17) is of further interest because it can be used to determine what fraction of the total C iv (or O vi mass) in the universe has been detected in the survey. This is achieved by changing the limits of the H i integration to match our column density cutoffs—$N_{\text{HI}} \geq 10^{13.6}$ for O vi and $N_{\text{HI}} \geq 10^{14.0}$ for C iv. According to this method, our limits probe 98.8% of the C iv mass and 90% of the O vi mass.
bands to photodissociate all of the nearby H$_2$, turning off the cooling source required to produce more stars. Thus the first major epoch of star formation and metal enrichment is thought to end at $z \sim 25$–$30$ (Mackey et al. 2003).

The resulting contribution to the intergalactic metal abundance depends on fairly uncertain models of the star formation rate prior to $z \sim 30$ and the efficiency with which the supernova ejecta can escape protogalactic halos and mix with distributed gas. In the figure we have shaded a region that reflects current estimates of the Population III metal production, for mixing gas. In the figure we have shaded a region that reflects current timescales (Rauch et al. 2001) at $z = 3$, which was calculated by applying a wind model to already completed numerical simulations. Again, the star formation and feedback parameters were adjusted to match local observations.

We confirm these authors’ finding that models with galactic winds are able to enrich the universe to the levels required by observations. Moreover, the model without winds grossly underestimates the cosmic metallicity, implying that essentially all of the heavy elements yet observed in the IGM were expelled from galaxies at relatively recent epochs, loosely $3 \leq z \leq 10$. This interpretation is consistent with measurements of turbulence in C iv systems at similar redshift, which indicate that metal-rich gas is often stirred on $10$–$100$ Myr timescales (Rauch et al. 2001).

Both wind models predict a mild correlation of increasing $Z/Z_\odot$ with density, and there is a weak indication that this trend follows the data. However, we again caution that our metallicity measurements are less accurate at $\rho/\bar{\rho} > 100$ (see $\S\S$ 3.1 and 3.2), and the correlation is very weak at lower densities. No such trend is seen in the C iv data. Many of the absorption lines in the range $\rho/\bar{\rho} = 100$–$300$ may in fact represent snapshots of the evolving winds themselves, in which case our photoionization models will probably overestimate [O/H]. These absorbers are complex and multi-phased, but their abundances have been crudely estimated at [O/H] $\geq -1.5$ (Simcoe et al. 2002), roughly consistent with the models.

Many of our points and upper limits fall well below the wind model predictions. This is most clearly seen at $\rho/\bar{\rho} \sim 8$–$50$ and may extend to lower densities; the lack of measurements at $\rho/\bar{\rho} \sim 1$–$2$ and $Z/Z_\odot \leq 10^{-7}$ is a selection effect, caused by the signal-to-noise–dependent detection thresholds of the data. Unfortunately, our data are not sensitive enough to probe $\rho/\bar{\rho} \leq 1$, where both wind models predict sharp abundance falloffs. With the large parameter space spanned by the wind and no-wind models, it seems likely that any plausible abundance pattern could be reproduced given a proper distribution of wind ejection velocities and metal content. The
model curves represent a volume average of $Z/Z_\odot$ at different densities; it will be interesting to test the dispersion in simulated metallicities with density against the data, although this is beyond the scope of this paper.

It appears that Population III–derived metals do not dominate the intergalactic distribution until one enters the underdense IGM. Even then, their spatial variation could be strongly affected if Population III star formation is strongly biased. It will be difficult to probe these metals using direct O VI measurements, since the fluctuations are at the $\sim1\%$ level from the continuum. Larger telescopes with very stable instrumentation will be required, and even then the effects of the Lyα forest may render such measurements impossible. A more promising approach for the far future will be to search for intergalactic O VI and O VIII absorption, since these are the dominant ionization states in the voids. However, the technical challenges involved in observing weak O VI and O VIII at high redshift will still be major obstacles for many years to come.

### 4.1. The Ultimate Closed Box?

We now consider a simple, global model of the chemical evolution of the universe. This model is analogous to chemical models of the galactic interstellar medium (ISM), but rather than focusing on the transport of mass and chemicals between stars and the ISM, we study the transport of mass and chemicals between galaxies and the IGM to determine the average chemical yield of galaxies in the early universe. As in galactic chemical evolution models, we assume that metals are recycled instantaneously, so for each $dM_{\text{gal}}$ of mass flowing into galaxies, a corresponding mass $y dM_{\text{gal}}$ of heavy elements is immediately returned to the IGM. The quantity $y$ is therefore a heavy-element yield for galaxy formation. The instantaneous approximation should work marginally well for the IGM, since the timescale for massive stellar evolution ($\tau \approx 10^{7}$ yr for a $M \approx 10^8 M_\odot$ star) and galactic winds ($\tau \approx 10^{-10}$ yr; Shapley et al. 2001) is shorter than cosmic timescales ($\tau \approx 10^{10}$ yr) at $z \approx 2.5$.

We define $\phi_{\text{gal}}$ as the rate of mass deposition into galaxies from the IGM; this mass may either be converted into stars or reside in the ISM of the galaxy. In each galaxy that is formed, a fraction $f$ of the ISM may be entrained in outflows and removed from the galaxy before it is substantially enriched. The exchange of mass due to galaxy formation is then governed by the following equations:

$$
\frac{dM_{\text{IGM}}}{dt} = -(1 - f_{\text{em}})\phi_{\text{gal}}
$$

$$
\frac{d}{dt}(ZM_{\text{IGM}}) = y(1 - f_{\text{em}})\phi_{\text{gal}} - Z(1 - f_{\text{em}})\phi_{\text{gal}},
$$

where $M_{\text{IGM}}$ is the total mass of gas in the IGM and, as usual, $Z$ is the fraction of $M_{\text{IGM}}$ bound up in heavy elements. By differentiating equation (20) and dividing by equation (19), we obtain

$$
M_{\text{IGM}} \frac{dZ}{dM_{\text{IGM}}} = -y.
$$

We have assumed that the total mass $M_{\text{tot}} = M_{\text{IGM}} + M_{\text{gal}}$ remains constant, i.e., there are no significant sources or sinks. We further assume the initial conditions $Z(t_0) = 0$, $M_{\text{gal}}(t_0) = 0$, $M_{\text{gas}}(t_0) = M_{\text{tot}}$. This is equivalent to the “simple closed box” model of galactic chemical evolution. Clearly, the IGM plus galaxies represents the ultimate closed system.

The solution to equation (21) is

$$
Z_{\text{IGM}} = y \ln \left( \frac{M_{\text{tot}}}{M_{\text{IGM}}} \right).
$$

We may use this relation to constrain the metal yield from galaxies in the era before $z < 2.5$. We have calculated $Z$ from the metallicity measurements provided above, noting that $Z_{\text{IGM}} = (10^{10/11}) Z_\odot$ with $(10^{10/11}) \sim 10^{22.2}$ and $Z_\odot = 0.02$, hence $Z_{\text{IGM}} = 1.3 \times 10^{-4}$. The quantities $M_{\text{tot}}$ and $M_{\text{IGM}}$ may be estimated using recent observations, first noting that

$$
\frac{M_{\text{tot}}}{M_{\text{IGM}}} \approx \frac{\Omega_b}{\Omega_{\text{Ly} \alpha}^*}.
$$

where $\Omega_{\text{Ly} \alpha}$ is the contribution to closure density from diffuse gas in the Lyα forest. The value $\Omega_b h^2 = 0.0224$ is now fairly secure from WMAP observations of the CMB (Spergel et al. 2003) and big bang nucleosynthesis observations (O’Meara et al. 2001). Our estimation of $\Omega_{\text{Ly} \alpha}$ is somewhat less certain. A lower bound on this quantity has been estimated using observations of the average flux decrement in the Lyα forest, either by matching the observations to simulations (Rauch et al. 1997c) or by requiring that the redshift and real-space extent of Lyα forest clouds are of similar magnitude (Weinberg et al. 1997). Rescaling Weinberg’s conservative estimate to a cosmology with $(\Omega_M, \Omega_\Lambda) = (0.3, 0.7)$ gives $\Omega_{\text{Ly} \alpha} h^2 > 0.20$, while Rauch finds $\Omega_{\text{Ly} \alpha} h^2 > 0.021$. It seems that there is basic agreement on a lower limit for the mass of the forest: $\Omega_{\text{Ly} \alpha} / \Omega_b > 0.92$.

We can estimate an upper limit for $\Omega_{\text{Ly} \alpha} / \Omega_b$ by noting that $\Omega_\Lambda \approx \Omega_{\text{Ly} \alpha} + \Omega_b + \Omega_{\text{DLA}} + \Omega_{\text{WH}} + \Omega_{\text{igm}}$, accounting for most known sources of baryons in the universe. The various terms represent the mass of the Lyα forest, stars, damped Lyα systems, warm-hot ($T = 10^4$–$10^5$ K) gas, and hot gas in galaxy clusters, respectively. To produce a conservative upper limit for $\Omega_{\text{Ly} \alpha}$, we subtract estimates of the mass density in damped systems and stars from $\Omega_b$. Of all the constituents of $\Omega_b$, these two are the ones most likely to represent local star-forming regions at high redshift.

The value of $\Omega_{\text{DLA}}$ has been estimated using extensive quasar surveys both at high and low resolution. We use the measurements in Storrie-Lombardi & Wolfe (2000) for $2 < z < 3$, $\Omega_{\text{DLA}} = 0.0009 \pm 0.0003 h^{-1}_70$. The stellar mass density $\Omega_\ast$ is much more difficult to measure since it is characterized in emission rather than absorption.

Dickinson et al. (2003) have used IR photometry to integrate directly the total $\Omega_\ast$ contained in luminous Lyman break galaxies from the HDF. Their photometry corresponds approximately to rest-frame optical wavelengths, which should be less subject to dust extinction and/or bursting star formation than rest-frame UV measurements. They estimate a conservative lower bound of $\Omega_\ast \approx 0.0002$ at $z \approx 2.5$, with their best estimate of the true value being a factor of 5 larger. Combining the most conservative estimate of $\Omega_b$ with the measured $\Omega_{\text{DLA}}$, we find $\Omega_{\text{Ly} \alpha} \lesssim \Omega_b - \Omega_{\text{DLA}} - \Omega_\ast = 0.0446$, leading to the final constraint

$$
0.92 \leq \frac{\Omega_{\text{Ly} \alpha}}{\Omega_b} \leq 0.97.
$$

DISTRIBUTION OF METALLICITY IN IGM

111
assuming $h = 0.71$. Entering these values into equation (22), the corresponding range for the galactic yield is

$$0.0015 \leq y \leq 0.0041.$$  \hfill (25)

In other words, typical galaxies in the early universe recycled 0.1%–0.4% of their input mass back into the IGM as heavy elements.

It is also interesting to compare the galaxy yield $y$ with the stellar yield interior to the galaxy, $y_*$. The stellar yield specifies the amount of metals released into the galaxy's ISM, $y_* dM_*$ for each $dM_*$ of stars formed. If we assume that a fraction $f_{ej}$ of the metals formed in a given starburst are ejected from the galaxy into the IGM, we may crudely relate the stellar and galactic yields for a galaxy:

$$y(M_* + M_{ISM}) = y_* M_*, f_{ej}. \hfill (26)$$

Here, $M_*$ and $M_{ISM}$ represent the amount of mass within the galaxy locked up in stars and gas, respectively. These terms may be rearranged to produce the following expression:

$$f_{ej} = \frac{y}{y_*} \left(1 + \frac{M_{ISM}}{M_*}\right). \hfill (27)$$

For bare stars, the ejected metal fraction is simply the ratio of the galactic and stellar yields; conversely, for galaxies with inefficient star formation more of the synthesized metals must escape in order to boost up the galactic yield. We saw in the previous section that most of the intergalactic enrichment is caused by relatively recent winds from star-forming galaxies. Since high-redshift galaxies show evidence for preferential enrichment by Type II supernovae, we estimate $y_*$ by integrating the supernova yields of Woosley & Weaver (1995) over an initial mass function, from 0.1 to 100 $M_\odot$. We have used various prescriptions for the IMF, including Salpeter (1955), Kennicutt, TAMBLYN, & Congdon (1994), and Miller & Scalzo (1979), which produce weighted yields ranging from $y_* = 0.001$ (Miller-Scalzo) to $y_* = 0.011$ (Kennicutt). The yield in the solar neighborhood is approximately $y_* \sim 0.02$. We may set a conservative lower bound on $f_{ej}$, using $y = 0.0015$ (eq. [25]) and $y_* = 0.011$, with the result

$$f_{ej} \approx 14\% \left(1 + \frac{M_{ISM}}{M_*}\right). \hfill (28)$$

The actual value of $f_{ej}$ is probably higher than 14%, since at earlier times less of the gas has been converted into stars, leading to a larger $M_{ISM}/M_*$. This could be mitigated to some extent if the high-redshift IMF is extremely top-heavy, which drives up $y_*$.

Despite our crude models and large uncertainties, the overall impression is that galaxies at high redshift are quite efficient at returning the metals they produce to the IGM. On average, they will eject over 1/10 of their nucleosynthetic by-products. Such vigorous recycling suggests that much of the star formation in early galaxies occurred in bursts, rather than a more quiescent, gradual mode that would allow them to retain their metals.

Observations of local starbursts indicate that the yields and ejection fractions we derive are fairly reasonable for star-forming dwarf galaxies. For example, the nearby dwarf NGC 1569 is driving a galactic wind that contains $\sim 34,000 M_\odot$ of oxygen at $Z \sim Z_\odot$ (Martin, KOBULNICKY, & Heckman 2002). The parent galaxy has a combined $M_{ISM} + M_* = 1 - 1.5 \times 10^8 M_\odot$. If we assume a solar mass fraction of oxygen relative to total heavy-element mass (0.378), the implied yield for this galaxy is $y = 0.0007$—roughly a factor of 2 below our lower limit for the high-redshift yield. The authors also find that the wind carries away nearly all of the metals produced by the starburst, while the neutral gas disk holds $\sim 5$ times more oxygen from prior periods of quiescent star formation, implying a metal ejection fraction of $f_{ej} \sim 15\%$–20% over the lifetime of the galaxy. We do not wish to overinterpret an isolated example when discussing the possible properties of all galaxies in the early universe. We simply note that similar objects at high redshift could produce and distribute the quantity of heavy elements seen in the IGM, provided their wind velocities are high enough to efficiently mix debris over large scales.

5. SUMMARY AND CONCLUSIONS

We have presented new observations of O vi and C iv absorption at $z \sim 2.5$, which were used to estimate the metallicity distribution function of the intergalactic medium. Seven quasar sight lines were used to measure O vi for lines with $N_{HI} \geq 10^{13.6}$; two of these with exceptionally high signal-to-noise ratios were also used to measure C iv for lines with $N_{HI} \geq 10^{14.0}$. These limits probe densities of $\rho/\bar{\rho} \sim 1.6$ relative to the cosmic mean. For each line in the samples, we estimated [O/H] and [C/H] by applying density-dependent ionization corrections to the measurements of $N_{HI}$, $N_{OVI}$, and $N_{CIV}$. We experimented with several prescriptions for the ionizing radiation background, eventually settling on a model that produced the best match between the distributions of [O/H] and [C/H]. This model is dominated by quasar light with an original spectrum of $F_\nu \propto \nu^{1.8}$, which has been reprocessed through the IGM, and normalized to a flux of $log F = -21.5$ at the $HI$ Lyman limit. Motivated by observations of metal-poor galactic halo stars, we also experimented with the radiation field to produce a relative intergalactic abundance of $[C/O] = -0.5$. A softer UV spectrum including galactic radiation was required to meet this criterion.

Our sample contains a mixture of detections and upper limits on the metallicity for each absorption line in the forest. The individual O vi and C iv lines are observed to scatter both above and below the trend of $[C, O/H] = -2.5$ observed in previous studies of the intergalactic metallicity, and several upper limits lie nearly an order of magnitude lower. Since the sample contains upper limits, we have used survival statistics to construct a Kaplan-Meier product limit estimate of the [O/H] and [C/H] distributions within the Ly$\alpha$ forest. For the O vi distribution, we carefully corrected for the effects of false positive identifications that might result from interloping $HI$ lines in the Ly$\alpha$ forest. Our basic results may be summarized as follows:

1. The mixture of heavy elements within cosmological filaments does not differ qualitatively in regions of high and low density (for roughly $1 \leq \rho/\bar{\rho} \leq 10 - 15$). We have not observed any significant variation in the [O/H] or [C/H] distribution that correlates strongly with $N_{HI}$, although there may be a weak correlation when we use our softest model for the ionizing background spectrum.

2. At $\rho/\bar{\rho} \approx 10 - 15$, we see evidence of a change in the trend of [O/H] relative to [C/H], which we interpret as the
onset of multiphased ionization structure in many of the stronger absorbers.

3. Roughly 30% of lines in the Lyα forest are enriched to abundances below [C, O/H] ≤ −3.5. Thus we have not detected evidence for a metallicity floor in the IGM. If such a floor exists, extrapolation of the cumulative abundance distribution suggests it would lie in the range −5 ≤ [C, O/H] ≤ −4, about a factor of 3 lower than the limits probed by our survey. Nevertheless, some portion of the cosmic volume is very metal-poor, even in regions with ρ/̄ρ ∼ 10.

4. The median abundance of the filaments is [C, O/H] = −2.82. By differentiating the cumulative abundance distribution, we obtain the probability density for [O/H] and [C/H], although we cannot construct the lowest metallicity portion of the distribution with our data. For the ∼70% of lines that we do measure, the distribution may be approximated as a Gaussian with mean ⟨[O/H]⟩ = −2.85 and σ = 0.75 dex. The distribution of Z/Z⊙ is therefore lognormal, with mean ⟨Z/Z⊙⟩ = 10^{−2.2}.

It is also instructive to express our results in terms of an enriched mass function, defined as the cumulative baryonic mass fraction of the universe that is enriched above a given abundance level. We place upper and lower bounds on the EMF by assuming either that the abundance pattern observed at ρ/̄ρ ≤ 1.6 extends to arbitrarily low density or that we have detected all heavy elements and that lower density clouds are chemically pristine. If the true pattern lies between these two extremes, then ∼50%–60% of all baryons in the universe have been enriched to [C, O/H] ≥ −3.5 by z ∼ 2.5. We have not calculated similar constraints for the enriched volume fraction, since even at these low column densities we only probe ∼5% of the spatial extent of the universe. Generally, then, our conclusions apply to the gas found in cosmic filaments at z ∼ 2.5, where most of the mass resides. We have not yet reached the voids which contain most of the cosmic volume.

We have examined our measurements in light of two established models for cosmic chemical enrichment. The first model describes metal production from the Population III stars postulated to form at z ≥ 30 from H2 cooling, and the second describes metal-laden superwinds that are driven from starburst galaxies at more recent epochs. A comparison of these models with our data suggests that Population III stars do not produce enough metals to enrich the cosmic filaments at observed levels.

Models incorporating galaxy outflows similar to those seen at low redshift can reproduce the observed average intergalactic metallicity. The significant scatter observed toward low Z/Z⊙ indicates that there may be local variations in the frequency or efficiency of these winds. Yet it seems likely that the models will be able to match these trends given proper tuning. The wind models predict a substantial decrease in the average metallicity at H i densities slightly below the threshold of our survey. The measurements presented herein do not have sufficient sensitivity to detect this decline; pixel-statistical methods may improve on this in the near future, and long-term prospects may include searches for intergalactic O vll and O vlll, which are the dominant ionization species at these densities.

To find regions of the universe whose metals are derived from Population III stars, it will be necessary to survey the cosmic voids. However, if Population III star formation is significantly biased then it is possible that the underdense IGM could remain nearly chemically pristine. The chemical enrichment of cosmological filaments is dominated by the debris of galactic outflows and therefore must have taken place relatively recently. Taken together with our estimates of the enriched mass function, this indicates that roughly half of all baryons have either been processed through a galaxy or mixed with material that has done so in the first 3 Gyr after the big bang.

Finally, we present a simple closed-box model of the chemical evolution of the universe. We use this model along with our metallicity measurements to estimate the average metal yield of galaxies prior to z = 2.5. For a galaxy, the metal yield is determined in part by the star formation rate and raw stellar yields, but also by the efficiency with which outflows can expel metals from the galaxy’s gravitational potential. We find that the typical galaxy ejects ∼0.1%–0.4% of its formed mass into the IGM as heavy elements. This amounts to at least ∼14% of the total quantity of metals synthesized within these galaxies. These yields are not qualitatively different from what is seen in some local dwarf starburst galaxies.

We gratefully acknowledge the assistance of F. Haardt in providing us with several different models of the X-ray/UV background spectrum in advance of the public release of his CUBA software package, as well as his graciousness in answering several questions about the details of the model calculations. This work would also not have been possible without several key software packages that have kindly been made available to the public by their authors. These include T. Barlow’s MAKEE data reduction software, R. Carswell’s VPFIT, G. Ferland’s CLOUDY, and E. Feigelson’s ASURV. We acknowledge helpful readings and/or discussions with M. Pettini, J. Schaye, and J. Prochaska, and D. Reimers provided advance information on several interesting targets. We thank the Keck Observatory staff for their assistance in carrying out the observations. Finally, we wish to extend special thanks to those of Hawaiian ancestry, for allowing us study the universe from their sacred mountain. W. L. W. S. and R. A. S. gratefully acknowledge financial support from NSF grants AST 99-00733 and AST 02-06067. M. R. is grateful for support through grant AST 00-98492 from the NSF and grant AR90213.01A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under NASA contract NAS5-26555.

APPENDIX A

A NOTE ON MODELS FOR THE UV/X-RAY IONIZING BACKGROUND

All of the models for the metagalactic ionizing background spectrum were provided to us by F. Haardt, using his CUBA package. This software performs calculations similar to those described in Haardt & Madau (1996), with some new features. The basic principle is to integrate the best available redshift-dependent luminosity functions from the literature to create an average source spectrum of galaxies and quasars at each redshift. Then the photons are statistically propagated through a parametrized...
model of the IGM to simulate absorption and reemission at important ionization edges. The newer models extend the range of the original Haardt & Madau (1996) spectra by including the X-ray background, which turns out to be quite important for O vi in the low-density IGM. We have already described in § 3.3 some of the uncertainties in the UV portion of the spectrum (e.g., the range in measurements of the spectral slope $\alpha$) and their effects on our results.

The model for the X-ray background is calculated independently from that of the UV/optical light in the new models. It is assumed to originate only from active galactic nuclei (AGNs), and its source function is calculated by integrating the X-ray luminosity function at each redshift. This function is assumed to evolve independently of the optical/UV luminosity function, and its redshift-dependent form is taken from Boyle et al. (1993). Seyfert I galaxies contribute flux at all X-ray wavelengths, since the IGM is exposed to the bare X-ray flux from the central AGN engine. The core of Seyfert II galaxies is covered by an obscuring torus that absorbs soft X-ray photons but transmits hard X-rays ($E \gtrsim 1$ keV). The hardness of the X-ray background is thus sensitive to the relative numbers of Seyfert I and II galaxies at each redshift.

The UV/X-ray background models use weighted combinations of Seyfert I and II X-ray spectra, constructed as described in Madau, Ghisellini, & Fabian (1994). The evolution in number ratio of Seyfert I to Seyfert II galaxies is estimated by assuming that AGNs with B-band luminosity above a given threshold are always Seyfert I galaxies, while those below are Seyfert II galaxies. This is normalized to locally observed type I/type II fractions. The models match observations of the UV and hard X-ray backgrounds at low redshift, within errors (Haardt & Madau 2001). The local soft X-ray metagalactic background is less well constrained, partly because of significant galactic foregrounds. This range turns out to be most important for our O vi results.

At $z \sim 2.5$, the UV/optical luminosity background is near its peak value over the history of the universe. Since the models calculate the type I/type II AGN fraction based on optical flux, this means that nearly all the AGNs at this redshift ($\gtrsim 95\%$) are counted as Seyfert I galaxies, and the soft X-ray background is quite high. The models are still uncertain, but it seems more likely that the soft X-ray backgrounds used here would err on the high side rather than the low, since essentially no dilution by type II AGNs is included at these redshifts. This affects our results in the sense that a higher soft X-ray flux will suppress O vi production, as described in Appendix B.

We have performed the entire analysis for several models of the ionizing background, retaining the HM1.80 model with log $J_{912} = -21.5$ since this produces the best match between the observed [O/H] and [C/H] distributions. The other models we tested included HM1.50 and HM1.55 slopes, with normalizations of log $J_{912} = -21.1$, $-21.4$, $-21.5$, and $-21.6$, and an HM1.80 model with H i ionizing flux from galaxies included. Our optimal normalization is slightly lower than estimates of $J_{912}$ made using the proximity effect at similar redshifts, although the discrepancy is only at the $\sim 1\sigma$ level. The field of X-ray population modeling at high redshift is rapidly evolving with the comprehensive surveys being undertaken by XMM and Chandra, and much better models of the high-redshift X-ray background should be forthcoming in the near future.

### APPENDIX B

#### EFFECTS OF THE X-RAY BACKGROUND ON DERIVED OXYGEN AND CARBON ABUNDANCES

It is seldom appreciated that for densities below $N_{H_1} \sim 3 \times 10^{14}$, the oxygen in the IGM is actually overionized relative to O vi—most atoms are in the O vii and O viii states (see Fig. 4). In photoionization equilibrium, the density of O vi is governed according to the equation

$$n_{O \, vi} \int_{138 \text{eV}}^{\infty} \frac{4\pi J(\nu)\sigma(\nu)}{h\nu} d\nu = n_T n_{O \, vi} A(T),$$

and likewise for other ionization states. Since at low densities $N_{O \, v} \ll N_{O \, viii}$, much more O vi is produced by recombination from O vi than photoionization of O v. Accordingly, the abundance of O vi is determined by the number of O vii ions available for recombination. At low densities, O vii and O viii are found in similar proportions and their ratio is sensitive to the background flux at the O vii $\rightarrow$ O viii ionization edge. This ionization energy is in the soft X-ray band (739 eV, or 17 Å; see Fig. 3), which leads to the counterintuitive result that the intergalactic O vi abundance is critically sensitive to the intensity of the soft X-ray background at low densities. A decrease in the soft X-ray background favors a higher O vi abundance and hence actually enhances O vi.

At densities above $N_{H_1} \sim 3 \times 10^{14}$, most oxygen is in either the O vi or O vii state. The ionic balance is then governed by the intensity of the UV background at the O vi $\rightarrow$ O vi and O vi $\rightarrow$ O viii ionization edges (109.5 and 89.5 Å, indicated in Fig. 3). In this regime, a decrease in the background results in fewer photons with sufficient energy to create O vi, thus lowering the predicted O vi column densities. Thus a substantial decrease in the X-ray background would cause our metallicities for the lowest density lines to move to lower values but leave the higher density lines basically unchanged—introducing a drop-off in metallicity below $N_{H_1} \sim 10^{14}$. Our best current models do not reveal such a trend, but the reader should bear in mind that a significant revision of the X-ray background at $z \sim 2.5$ could affect this result.

### REFERENCES

Abel, T., Bryan, G. L., & Norman, M. L. 2002, Science, 295, 93
Adelberger, K. L., Steidel, C. C., Shapley, A. E., & Pettini, M. 2003, ApJ, 584, 45
Aguirre, A., Hernquist, L., Schaye, J., Katz, N., Weinberg, D. H., & Gardner, J. 2001, ApJ, 561, 521
Aguirre, A., Schaye, J., Kim, T.-S., Theuns, T., Rauch, M., & Sargent, W. 2004, ApJ, 602, 38
Aguirre, A., Schaye, J., & Theuns, T. 2002, ApJ, 576, 1
Akerman, C., Carigi, L., Nissen, P., Pettini, M., & Asplund, M. 2004, A&A, 414, 931
Allende Prieto, C., Lambert, D. L., & Asplund, M. 2001, ApJ, 556, L63
———. 2002, ApJ, 573, L137
Asplund, M. 2003, preprint (astro-ph/0302409)
Bergeron, J., Aracil, B., Petitjean, P., & Pichon, C. 2002, A&A, 396, L11
Boksenberg, A., Sargent, W. L. W., & Rauch, M. 2003, preprint (astro-ph/0307557)
