A SEARCH FOR OXYGEN IN THE LOW-DENSITY Lyα FOREST USING THE SLOAN DIGITAL SKY SURVEY

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ABSTRACT

We use 2167 Sloan Digital Sky Survey quasar spectra to search for low-density oxygen in the intergalactic medium (IGM). Oxygen absorption is detected on a pixel-by-pixel basis by its correlation with Lyα forest absorption. We have developed a novel locally calibrated pixel (LCP) search method that uses adjacent regions of the spectrum to calibrate interlopers and spectral artifacts, which would otherwise limit the measurement of O vi absorption. Despite the challenges presented by searching for weak O vi within the Lyα forest in spectra of moderate resolution and signal-to-noise, we find a highly significant detection of absorption by oxygen at 2.7 < z < 3.2 (the null hypothesis has a \( \chi^2 = 80 \) for nine data points). We interpret our results using synthetic spectra generated from a log-normal density field assuming a mixed quasar–galaxy photoionizing background and that it dominates the ionization fraction of detected O vi. The LCP search data can be fit by a constant metallicity model with [O/H] \( \sim -2.15±0.07 \), but also by models in which low-density regions are unenriched and higher density regions have a higher metallicity. The density-dependent enrichment model by Aguirre et al. is also an acceptable fit. All our successful models have similar mass-weighted oxygen abundance, corresponding to \([O/H]_{MW} = -2.45±0.06\). This result can be used to find the cosmic oxygen density in the Lyα forest, \( \Omega_{\text{O}_2,\text{IGM}} = 1.4(±0.2) \times 10^{-6} \approx 3 \times 10^{-9} \Omega_b \). This is the tightest constraint on the mass-weighted mean oxygen abundance and the cosmic oxygen density in the Lyα forest to date and indicates that it contains \( \approx 16\% \) of the total expected metal production by star formation up to \( z = 3 \).

Key words: galaxies: formation – intergalactic medium – quasars: absorption lines

Online-only material: color figures

1. INTRODUCTION

The intergalactic medium (IGM) is the spatially undulating reservoir of baryons from which all galaxies form. During the dark ages, before formation of the first stars, this reservoir was composed of elements in proportions arising from big bang nucleosynthesis: hydrogen, helium, and trace amounts of lithium and beryllium. Metals have been produced since the formation with extragalactic winds (e.g., Mac Low & Ferrara 2000; Schaye et al. 2003; Pieri et al. 2006). Progress has also made reproducing this enrichment in models of galaxy formation with extragalactic winds (e.g., Mac Low & Ferrara 1999; Madau et al. 2002; Oppenheimer & Davé 2004) are directed toward finding metals distributed throughout the forest without identifying individual systems. In the case of the search for O vi, they are limited by cosmic variance in the contaminating Lyman lines and noise. The standard pixel (SP) correlation search (sometimes known as “pixel optical depth”) for O vi (e.g., Aguirre et al. 2002, 2008, hereafter A08; Pieri & Haehnelt 2004) is not, however, a suitable approach for the detection of metals in the SDSS Lyα forest because of the moderate resolution (\( R = \lambda / \Delta \lambda = 1800 \)) and signal-to-noise ratio (S/N). A pixel correlation search is possible in principle, but modifications to the approach are required. We have developed a tailored pixel method, which we refer to as the locally calibrated pixel (LCP) search method. Our statistical analysis of O vi absorption in the low-density IGM complements the direct search for strong O vi absorption in the same spectra (Frank et al. 2010a, 2010b).

While interpretation of pixel searches using high-resolution, high S/N spectra is more straightforward, the small amount of high-quality data leaves the conclusions subject to uncertainty owing to cosmic variance. The use of the large number of SDSS spectra (>2000 used here) with the LCP search method offers...
a large reduction in this variance (and potentially an increase in overall S/N).

All pixel correlation searches require simulations in order to ascertain the gas mass densities of enriched systems, the number densities of ions required, the ionization fraction (and so metallicity of those systems), and the impact of observational limitations and errors. This is particularly important here as the resolution of the SDSS spectra introduces a significant uncertainty in the gas mass density of enriched systems. To address this issue and interpret our search results, we have simulated each SDSS spectrum used 10 times for various models of oxygen enrichment, totaling more than 4.5 million synthetic SDSS spectra.

Noise levels in individual SDSS spectra are higher than those of high-resolution spectra used in previous studies, and with this (along with the lower resolution) comes more uncertainty in the continuum fitting. This problem becomes increasingly severe at the blue end of the spectrograph, where most of the signal of the continuum lies. The correlation search technique that we outline below is calibrated to the flux level in the local spectrum to take into account variations in the continuum (hence the name “locally calibrated pixel search”).

This paper is organized as follows. In Section 2, we describe the data set used. In Section 3, we describe the LCP search method and results. In Section 4, we describe our interpretation of these results using simulated spectra, and in Section 5 we describe our measure of mass-weighted mean oxygen abundance and the cosmic oxygen density. This is followed by a discussion of the ionization corrections and other searches and, finally, the conclusions.

Following standard notation, we write \([\text{O}/\text{H}] = \log(\text{O}/\text{H}) - \log(\text{O}/\text{H})_\odot\), where \(\text{O}/\text{H}\) is the ratio of oxygen to hydrogen (by number). We adopt \(\log(\text{O}/\text{H})_\odot = -3.13\) estimated for the solar envelope by Grevesse et al. (1996), for ease of comparison with other studies of oxygen enrichment of the IGM. While some analyses based on more detailed stellar atmosphere models have argued for lower \(\log(\text{O}/\text{H})_\odot\) (Asplund et al. 2005; Caffau et al. 2008), stellar interior models and helioseismology strongly support the Grevesse et al. abundance scale (Busé & Antia 2004; Delahaye & Pinsonneault 2006). For values of solar abundance taken from Asplund et al. (2005) and Caffau et al. (2008), scale our \([\text{O}/\text{H}]\) results by +0.21 and +0.11, respectively.

2. THE SAMPLE OF SPECTRA

The \(\text{O}\,\text{VI}\) doublet starts to become visible at the blue end of SDSS quasar spectra at redshifts of \(z_{\text{abs}} \geq 2.7\). Hence, we retrieved QSO spectra from the SDSS Third Data Release (DR3: Abazajian et al. 2005) beyond this lower boundary redshift using the QSO Absorption Line Systems (QSOALS) project database (York et al. 2006).

The spectra we used were fitted with an automatic continuum procedure developed by Arlin Crotts and used in the QSO absorption line data base of the SDSS QSOs (York et al. 2006). The continuum is derived by discarding absorption-contaminated pixels until the variance in the remaining pixels corresponds to that prescribed by the noise model for the measurement. This provides a smoothed estimate of the spectrum, forming a “continuum” for the measurement of narrow lines over a range of pixels that varies with the large-scale variations in the SDSS spectrum. At a minimum (e.g., near narrow emission lines from the QSO or the sky, or at the steep drop at the edge of a broad absorption line), the smoothing is over a 20 pixel region (between 18 Å and 24 Å in the forest used here). In smooth regions of the spectrum, outside the Ly\(\alpha\) forest, the method produces continua accurate to about 2% when the photon noise is small enough to permit such precision. The method produces a reasonable estimate for the continuum in the Ly\(\alpha\) forest for our purposes. Note that the rare cases of a Ly\(\alpha\) BAL or the more common cases of an \(\text{O}\,\text{VI}\) BAL will be fitted away and this is a desirable feature for our purposes.

There are rarely rapid continuum changes to be expected over 30 Å, and certainly no significant nonlinear trends. This gives us a good enough continuum for application of a locally calibrated continuum for the \(\text{O}\,\text{VI}\) absorption measurement, as described in Section 3. The continuum-fitting method may subtract large-scale structures in Ly\(\alpha\) absorption on scales >2800 km s\(^{-1}\), but this effect will be minimal as indicated by the good agreement between the probability distribution function (PDF) of the Ly\(\alpha\) optical depth in the data and the models as shown in Figure 4 below. This continuum-fitting method results in a \(\sim 16\%\) systematic underestimate of the continuum (and so an overestimate of the transmitted flux) measured as an equivalent underestimate of the mean flux decrement in the sample with respect to values in the literature (e.g., McDonald et al. 2000; Kim et al. 2007). We have taken this into account by introducing the same systematic to our simulations as described in Section 4.1.

We do not exclude BAL quasars from the sample used in this study. We have tested the impact of these BAL QSOs by performing the LCP search excluding the 430 QSOs that are identified by Gibson et al. (2009) as BAL QSOs and fall into our sample. The impact of this modification is much smaller than the 1σ error bars.

As can be seen in Figure 3 of Frank et al. (2010a), the majority of the sources have \(i\) band magnitudes between 19.5 and 20.5. The average S/N of the spectra within the region of interest for us is only about 2.5, which is much less than the overall S/N of the spectrum, since the flux levels within the Ly\(\alpha\) forest are much lower than those beyond it. This figure also shows the distribution of these average S/N values with the emission redshifts of the sample sources. Particularly toward higher redshifts, it is apparent that the increasing density of the forest and the general faintness of the sources lead to a severe decrease in the S/N.

In order to ensure that the noise characteristics of the sample can be adequately reproduced in the simulated spectra, we have performed an analysis of the behavior of the noise in the full data set at every observed wavelength. The uncertainty in the flux measurement, \(\sigma(f, \lambda)\), is the sum in quadrature of two terms, the readout noise of the detector system and the photon noise. The former is a Gaussian distribution with \(\sigma_{\text{ro}}(\lambda) = k_1\), where \(k_1\) is a constant at a particular wavelength, independent of the incident flux. The latter is a Poisson distribution with \(\sigma_{\text{ph}}(f, \lambda) = k_2 \times \sqrt{f_\lambda}\), where \(k_2\) is a constant at a particular wavelength.

At each wavelength, we fit the distribution of the error estimate in the flux provided by the QSOALS database with this two-parameter model, and hence are able to describe the complete noise characteristics of the underlying SDSS sample by the wavelength-dependent \(k_1(\lambda)\) and \(k_2(\lambda)\). Figure 1 shows an example of the noise distribution as a function of the estimated flux, \(f_\lambda\), at a specific wavelength. We have used this formalization of the noise characteristics to produce a realistic representation of observing conditions in synthetic spectra as described in Section 4.1. This figure also illustrates how the
noise may always be characterized as a Gaussian distribution, since the (Gaussian) readout noise dominates where the Poisson nature of the photon noise is significant.

3. THE LOCALLY CALIBRATED PIXEL SEARCH

Pixel correlation searches for the detection and investigation of metal enrichment in the IGM have, until now, been limited to high-resolution quasar absorption spectra. In these spectra, the optical depth of every pixel of the Lyα forest can be characterized as a measure of the density in the IGM. Where the Lyα absorption is saturated (and so the measured Lyα optical depth measure is noisy), higher order Lyman lines can be used to reconstruct the Lyα optical depth.

Ionization species other than neutral hydrogen can produce their own forest of absorption. In particular, there is a forest of five times ionized oxygen (Ovi) and a forest of three times ionized carbon (Civ). These metal line forests can also be dealt with on a pixel-by-pixel basis at each redshift. Hence, one can collect Lyα and Ovi or Civ pixel pairs, bin by Lyα optical depth, and one would see a clear trend in metal line optical depth (using only basic assumptions of ionization and metallicity, which we will return to throughout this paper).

Difficulties arise when the measured optical depth of the metal pixels is not entirely due to the intended species. Various techniques have been used in the SP search to minimize the degree of contaminating absorption, but it cannot be removed entirely, and it tends to dominate where absorption is weakest. These techniques involve correction of contaminating Lyman series lines in the Ovi region of the spectra by removing expected higher order lines (based on the Lyα absorption at the same redshift and longer wavelength), or the use of both Ovi lines to derive a minimally contaminated signal.

As is done in all pixel correlation searches in quasar spectra, we compared the absorption from a species at a fixed redshift with the absorption from another species at the same redshift. Where the absorption is correlated, a detection is found. In this analysis, we search for Ovi (λ1032 Å) absorption correlated with Lyα (λ1216 Å) absorption and make no use of the Ovi doublet line (Oviλ) at 1038 Å. We produce these pixel pairs for a range of redshifts and on a grid set by the spectral binning of the Ovi pixels (the Lyα absorption is interpolated). Nearby pixels with a wavelength close to the Ovi wavelength are used to characterize continuum errors and contaminating absorption. This procedure is explained in more detail below.

We have simplified the algorithm in recognition of the fact that there are features of the SP search that are unsuitable in the context of our local calibration method. These techniques are directed toward subtracting contamination. We do not seek to remove contaminating absorption; as described above, we characterize it, and, as shall be seen below, the LCP analysis does this automatically.

The lower redshift limit for every quasar in the sample is set by the blue end of the spectrograph (around 3800 Å) or the Lyγ line at the quasar redshift, whichever results in a higher minimum redshift. We discard pixels with Lyγ as they provide little extra information but modify the distribution of absorbers in Ovi signal enough to introduce unnecessary uncertainty. Note that this requirement also means that no absorption at the Lyman limit is possible. We rule out regions within 5000 km s⁻¹ of the QSO emission redshift to eliminate most effects due to the QSO and its environment (Wild et al. 2008). This sets the upper redshift limit and also results in an Ovi signal (since the separation between Ovi and Lyβ forest (since the separation between Ovi and Lyβ absorption at the emission redshift is 1804 km s⁻¹ in the Ovi frame).

We combine the pixel pairs for each QSO into one combined sample for all the SDSS spectra in the required redshift range producing over a million pixel pairs. The redshift distribution of these data is shown in Figure 2.

3.1. H i Absorption

The determination of the degree of H i absorption is largely unchanged from the SP search. The optical depth to Lyα absorption τLyα is determined for each pixel. We make the same

![Figure 1. Example of the noise characteristics of the sample spectra at 5000 Å. The black points are the estimated noise levels in real flux, σ(fά), vs. the flux at 5000 Å. The noise can be separated into two components, the detector-dependent readout noise, σro, and the flux-dependent photon noise, σph. The dotted red line shows the two-parameter fit to the data, as described in the text. The dashed black lines indicate the location of the noise if it were purely dominated by the Poisson statistics of the photon noise with 5, 10, and 20 counts. Where the photon noise dominates, the counts are clearly above 20, and so this Poisson distribution is well described by a Gaussian approximation. Hence, the noise distribution is Gaussian at all levels of flux. We have confirmed this for the complete wavelength range covered by SDSS. (A color version of this figure is available in the online journal.)](image-url)
noise requirement as other searches: the flux transmission must be \( \sigma_{\text{noise}}/2 \) from either the zero level or the continuum, where \( \sigma_{\text{noise}} \) is the continuum-scaled error estimation in the continuum-fitted spectrum. This is a rather strict criterion in the context of the SDSS sample and discards \( \approx 20\% \) of pixel pairs. We do not attempt to extend the analysis to the higher density regime, where Ly\( \alpha \) absorption is saturated, by using higher order Lyman lines to derive the Ly\( \alpha \) optical depth. This is a regime to which other methods are better suited (Frank et al. 2010a, 2010b). It should be noted, we assume that all O\( \Pi \) other methods are better suited (Frank et al. 2010a, 2010b).

The large amount of data at our disposal allows us to aggressively discard less reliable measures of \( \tau \) assumption. It should be noted, we assume that all O\( \Pi \) other methods are better suited (Frank et al. 2010a, 2010b).

### 3.3. The Aggregation of Pixel Pairs

Since we have a large sample of spectra with comparable characteristics and a limited redshift range, we aggregate all acceptable pixel pairs from all our spectra. We use pixels in a redshift range of \( 2.7 < z < 3.2 \) both to keep our data as homogeneous as possible and to limit ourselves to the subset that provides the strongest signal. This limits us to 2167 QSO spectra in our sample, out of the 5767 \( z > 2.3 \) quasar spectra in SDSS DR3.

Once we have a list of \( \tau_{\text{O\Pi}} - F_{\text{O\Pi}}/F_t \) pairs, as set out above, we bin them by their \( \tau_{\text{O\Pi}} \) and take the median of the \( \tau_{\text{O\Pi}} \) and the \( F_{\text{O\Pi}}/F_t \) in order to produce our final search for O\( \Pi \) via. We use the median as an outlier- and noise-resistant measure of the typical absorption.

Since \( \tau_{\text{O\Pi}} \) and \( \tau_t \) are drawn randomly from the same distribution, and (where the local pixel is sufficiently close) \( f_{\text{c},l} \approx f_t \), the median(\( F_{\text{O\Pi}}/F_t \)) is a quantity that characterizes correlated O\( \Pi \) absorption normalized to a factor dependent on the mean O\( \Pi \) via optical depth. The precise level of this normalization is unimportant in the following results; as with other pixel correlation searches, a statistically significant correlation is required for a detection of metals. It is, however, broadly indicative of the average O\( \Pi \) absorption level. It is also notable that this level is recovered in the null tests that follow.

### 3.4. Choice of Local Pixels

For local pixels we chose those that are (1) sufficiently far away from the O\( \Pi \) search pixel to avoid comparison with pixels within the same extended complex associated with the same enriched region, (2) sufficiently close to avoid producing spurious correlations with the Ly\( \beta \) and O\( \Pi b \) absorption, and (3) sufficiently close to measure the same continuum level. The second requirement ensures that the third requirement is satisfied. Ly\( \beta \) is stronger and correlated over a larger velocity range compared with O\( \Pi b \), hence we design our choice of local pixels for avoidance of this line. We also require that the choice of local pixels is mirrored on each side of the search pixel in order to cancel continuum level error trends across the line.

We take 18 local pixels in total for this analysis: the 9th to 18th pixel to that on a locally calibrating pixel is

\[
F_{\text{O\Pi}}/F_t = \frac{f_t \exp[-\tau_{\text{O\Pi}}] \exp[-\tau_t] + \text{noise}}{f_{\text{c},l} \exp[-\tau_{\text{O\Pi},l}] \exp[-\tau_t] + \text{noise}^l}.
\]

where \( f_t \) is the flux level at the continuum, \( \tau_{\text{O\Pi}} \) is the optical depth to O\( \Pi \) via absorption, “noise” is the Gaussian instrumental noise, the subscript “I” indicates a local value, and the subscript “c” refers to uncorrelated contaminating absorption. This uncorrelated absorption is dominated by Ly\( \alpha \) and Ly\( \beta \) absorption, but it also includes contamination by the second member of the O\( \Pi \) doublet \( (\tau_t = \tau_{\text{Ly}\alpha} + \tau_{\text{Ly}\beta} + \tau_{\text{O\Pi b}}) \), all at different redshifts. \( \tau_{\text{O\Pi vi}} \) is the local O\( \Pi \) via absorption, which is also uncorrelated where the appropriate local pixels are used, as we shall argue in Section 3.4.

Multiple local pixels are used, and each one provides a new measure of spectral characteristics local to our required O\( \Pi \) via pixel. Operationally, we treat each local pixel as providing a new measure of \( F_{\text{O\Pi}}/F_t \) and so a new pixel pair of \( \tau_{\text{Ly}\alpha} - F_{\text{O\Pi}}/F_t \). In this way, the final statistical error is dominated by the number of Ly\( \alpha \)–O\( \Pi \) via pixels and not by the noise in the local pixels.

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**Figure 2.** Redshift distribution of pixel pairs available for the analysis in the SDSS sample. The lower envelope is set by the lowest redshift systems observable in O\( \Pi \) at the blue end of the spectograph. The upper envelope is set by 5000 km s\(^{-1}\) below the emission redshift of QSOs in the sample.
et al. 2003, 2005; Pieri et al. 2006; Scannapieco et al. 2006), so these results seem reasonable for O vi. Correlations in Lyβ extend over greater scales than this due to large-scale structure (McDonald et al. 2006), but such lines are somewhat stronger than expected here and our test searches confirm this. In principle C II(λ1036 Å) could produce correlated absorption within our calibrating pixel range, but in practice it appears to be too weak.

In test searches, we detected the doublet line O vi b at a consistent level with that of the O vi a line. Since this line merely constitutes a parallel but less sensitive measure of O vi that does not contribute to the search algorithm, we have not used this information.

3.5. O vi Search Results

Once the pixel pairs required are combined and binned by their τ_{Lyα}, we find their medians to plot F_{O vi}/F_{i} versus τ_{Lyα} as shown in Figure 3. We required that more than 200 pixel pairs be available for a bin to be used. In all panels, the error bars are produced by bootstrap resampling with 100 realizations and a bootstrap element of 1 SDSS QSO. The median is found for every realization, and the error bars are then taken to be the 1σ deviation in the distribution of medians.

Figure 3 shows F_{O vi}/F_{i} versus τ_{Lyα} using pixels in the redshift range 2.7 < z < 3.2. There is a clear correlation between τ_{Lyα} and F_{O vi}/F_{i}, and this correlation extends to all measured values of τ_{Lyα}. There is both excess O vi absorption in pixels with strong Lyα absorption and a deficit of O vi absorption (F_{O vi}/F_{i} > 1) in pixels where Lyα absorption is weak.

The null test shown in Figure 3 is performed using the same technique as set out above with the only modification that the rest-frame wavelength for correlations is no longer the O vi a rest-frame wavelength (1032 Å) but λ = 1047 Å. As can be seen, the search approach passes the null test by recovering the expected result of F_{1047} ≈ F_{i}, where neither an excess nor a deficit in absorption is seen as no signal being present.

Figure 3 shows the main observational result of this paper. In high-resolution spectra there is an approximate one-to-one relation between τ_{Lyα} and gas overdensity ρ/ρ_0 (Rauch et al. 1997; Croft et al. 1998; Weinberg et al. 1998). At SDSS resolution this is no longer the case, so the interpretation of this result in terms of enrichment of the IGM must rely on synthetic spectra drawn from an underlying physical model.

4. INTERPRETATION USING SYNTHETIC SPECTRA

4.1. Production of Synthetic Spectra

We use an approach for the production of simulated line-of-sight density distributions that was set out in Pieri & Haehnelt (2004). We restate this method here, but for a full description refer to Pieri & Haehnelt. We use cosmological parameters consistent with WMAP5 (Komatsu et al. 2009) (Ω_m = 0.268, Ω_{Λ} = 0.732, Ω_{b} = 0.0441, σ_{8} = 0.776, and H_0 = 70.4 km s^{-1} Mpc^{-1}) in these simulations.

We start with a three-dimensional power spectrum of dark matter density fluctuations taken from Efstathiou et al. (1992). This is normalized using the cosmological parameter, σ_{8} (the amplitude of clustering on an 8 h^{-1} Mpc scale at the present epoch), and the linear growth of structure at the required redshift. A Jeans length filtering (∼0.9 h^{-1} Mpc moving in the surveyed redshift range) to remove structure on small scales is used to describe baryonic pressure effects.

Two one-dimensional power spectra are produced by integration of the three-dimensional power spectrum (Kaiser & Peacock 1991), and Gaussian random realizations of structure are generated. These one-dimensional realizations of structure are combined to produce coupled density contrast and velocity fields. This velocity field, v(x), is a non-dynamical approximation based on the linear density field, δ(x). For more details on this approach see Bi & Davidsen (1997) and references therein.

Further following the method of Bi & Davidsen (1997), we convert our linear density field to a lognormal distribution, using the mapping

$$\rho/\bar{\rho}(x) = \exp[\delta(x) - \langle \delta^2 \rangle / 2],$$

which they find reproduces the PDF of nonlinear structures. It should be noted that this method fails to reproduce the clustering of nonlinear structures (Viel et al. 2002). The density field has a resolution of 0.01 Mpc comoving, which substantially oversamples the resolution required by the SDSS sample but is adopted in order to ensure that the physics of the IGM is well described.

The temperature of the IGM in these simulations is set by the balance between photoionization heating and adiabatic cooling and follows the power-law relation

$$T = T_0 (\rho/\bar{\rho})^{0.4}$$

(Hui & Gnedin 1997), where ρ/\bar{\rho} is the overdensity and the temperature at mean density is T_{0} = 2 × 10^4 K. The temperature is required to calculate the Doppler parameter for this gas.

For a given set of cosmological parameters and a helium fraction of 0.242 by mass, it is trivial to calculate the hydrogen density. Oxygen is added in quantities as described in the following section. The ionization fractions of hydrogen and oxygen are calculated using CLOUDY version 08.00 (Ferland et al. 1998) and the Haardt & Madau (2001) (hereafter HM01)
quasar and galaxy UV background model (designated QG) with a 10% escape fraction from galaxies. While these calculations do take into account collisional ionization, the lack of heating other than via photoionization in our simulations makes the conditions for it to occur rare. As such, we predominately interpret the detection of 

$$\frac{O}{H}$$

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$$\alpha = \frac{O}{H}$$

will be overwhelmingly photoionized and we find this regime dominates our measured 

$$\alpha = \frac{O}{H}$$

(see Section 4.3).

We calculate the optical depths for 

$$\tau(v) = \frac{\pi e^2 \lambda f}{m_e c H} \int n(v') \exp \left[ -\left( \frac{v - v_0}{b(v')} \right)^2 \right] dv',$$

where the transition-dependent parameters are the rest-frame wavelength \(\lambda\), the oscillator strength \(f\), the number density of absorbing particles \(n\), and the Doppler parameter \(b\). \(H\) is the redshift-dependent Hubble parameter, \(v\) is the line-of-sight velocity, \(v_0\) is the velocity of the Hubble flow, \(e\) is the electron charge, \(m_e\) is the electron mass, and \(c\) is the speed of light. This is integrated over the narrow range of velocities that contribute significantly to the calculation (effectively a few times the Doppler parameter).

We add instrumental broadening to match the SDSS spectral resolution. As stated in Section 2, we have performed an analysis of the characteristic \(\sigma_f\) (f, \(\lambda\)) in our sample, and we use this to add Gaussian noise to the spectra. In order to achieve this we use the continuum level in the real spectra to rescale the simulated transmission flux to a flux, \(f_\lambda\). The photon noise is well described by a Gaussian distribution where it dominates, and the readout noise is also a Gaussian, so treating the combined noise \(\sigma_{f, \lambda}\) as a Gaussian is a good approximation (Section 2). Finally, we rescale our transmitted fluxes up by 16% in line with the systematic underestimate of the continuum in our sample (Section 2).

The intensity of the UV background was renormalized (see Section 6.1) to provide a match of the PDF of optical depths derived from our synthetic spectra with that of the observed sample. We obtain agreement with an ionization rate of \(\Gamma = 13\times10^{-13}\) s\(^{-1}\) as is shown in Figure 4. The quality of this agreement is sufficiently good to populate the bins in \(\tau_{\alpha}\) with statistics that are representative of the LCP search in the data.

### 4.2. The Monte Carlo Approach

For every oxygen abundance pattern, we simulate a full suite of 2167 SDSS QSO spectra and do this 10 times. For each one we perform an LCP search for \(\alpha\), and the resultant \(F_{\alpha}/F_i\) versus \(\tau_{\alpha}\) is averaged over the 10 suites to obtain a model prediction (so that the quality of the fit between the model and observed LCP searches is dominated by the error in the observed search). We have used this set of 21,670 line-of-sight density distributions with varying levels of oxygen abundance to interpret our observations. Each of these lines of sight requires the simulation of a one-dimensional density distribution of length around 1000 h\(^{-1}\) Mpc. The production of this quantity of data is not practical with fully numerical simulation methods given current computer processor limitations. This underlines the value of the analytical technique described in the previous section. Two hundred and twelve models of oxygen enrichment have been tested, totaling more than 4.5 million synthetic spectra produced.

In the following analysis, we do not include the measure at \(\tau_{\alpha, 15.5}\) \(\approx 3.3\) (see Figure 3). The inclusion of this point results in poor agreement with the models. This is consistent with the findings of A08 that high \(\tau_{\alpha}\) absorption results from a different population of \(\alpha\) absorbers that are most likely collisionally ionized.

### 4.3. Comparison of Real and Synthetic Spectra

We add oxygen with a constant \([O/H]\) to our synthetic spectra and have varied this \([O/H]\) to find a good fit to the observed search. Figure 5 shows a comparison of the observed search (filled circles) with four models. Once more we see that our LCP search responds well to the null test (solid line) by returning a result of \(F_{\alpha} \approx F_i\) when no oxygen is added (reduced noise is also a Gaussian, so treating the combined noise \(\sigma_{f, \lambda}\) as a Gaussian is a good approximation (Section 2). Finally, we rescale our transmitted fluxes up by 16% in line with the systematic underestimate of the continuum in our sample (Section 2).

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### 4.2. The Monte Carlo Approach

For every oxygen abundance pattern, we simulate a full suite of 2167 SDSS QSO spectra and do this 10 times. For each one we perform an LCP search for \(\alpha\), and the resultant \(F_{\alpha}/F_i\) versus \(\tau_{\alpha}\) is averaged over the 10 suites to obtain a model prediction (so that the quality of the fit between the model and observed LCP searches is dominated by the error in the observed search). We have used this set of 21,670 line-of-sight density distributions with varying levels of oxygen abundance to interpret our observations. Each of these lines of sight requires the simulation of a one-dimensional density distribution of length around 1000 h\(^{-1}\) Mpc. The production of this quantity of data is not practical with fully numerical simulation methods given current computer processor limitations. This underlines the value of the analytical technique described in the previous section. Two hundred and twelve models of oxygen enrichment have been tested, totaling more than 4.5 million synthetic spectra produced.

In the following analysis, we do not include the measure at \(\tau_{\alpha, 15.5}\) \(\approx 3.3\) (see Figure 3). The inclusion of this point results in poor agreement with the models. This is consistent with the findings of A08 that high \(\tau_{\alpha}\) absorption results from a different population of \(\alpha\) absorbers that are most likely collisionally ionized.

### 4.3. Comparison of Real and Synthetic Spectra

We add oxygen with a constant \([O/H]\) to our synthetic spectra and have varied this \([O/H]\) to find a good fit to the observed search. Figure 5 shows a comparison of the observed search (filled circles) with four models. Once more we see that our LCP search responds well to the null test (solid line) by returning a result of \(F_{\alpha} \approx F_i\) when no oxygen is added (reduced noise is also a Gaussian, so treating the combined noise \(\sigma_{f, \lambda}\) as a Gaussian is a good approximation (Section 2). Finally, we rescale our transmitted fluxes up by 16% in line with the systematic underestimate of the continuum in our sample (Section 2).

The intensity of the UV background was renormalized (see Section 6.1) to provide a match of the PDF of optical depths derived from our synthetic spectra with that of the observed sample. We obtain agreement with an ionization rate of \(\Gamma = 13\times10^{-13}\) s\(^{-1}\) as is shown in Figure 4. The quality of this agreement is sufficiently good to populate the bins in \(\tau_{\alpha}\) with statistics that are representative of the LCP search in the data.
$\chi^2 = 10$). In the best-fitting case, $[O/H] = -2.15$ (dashed line), we find good agreement with the observed result, and there is no need for the addition of more parameters in the fit. Models with constant $[O/H] = -2.0$ (dotted line) or $[O/H] = -2.3$ (dot-dashed line) are clearly ruled out and indicate that the LCP search in the SDSS sample is sensitive to small changes in the abundance of oxygen in the IGM.

We can quantify the quality of the fit by using the $\chi^2$ test where error bars are given by bootstrapping of the observed data. We have done this for varying $[O/H]$ as shown in Figure 6 (solid line). The $1.5\sigma$ and $2\sigma$ levels are shown as dotted lines. It is clear that our best-fitting model with $[O/H] = -2.15$ constitutes an adequate fit to the observed search. We can give this measure a $2\sigma$ confidence interval of $[O/H] = -2.15^{+0.07}_{-0.09}$. These models constitute the range of constant $[O/H]$ models favored by the LCP search. The quality of this fit is suggestive of an underlying density dependence to the $[O/H]$ signal (as found by A08), but the statistics do not warrant a two-parameter fit.

We may not be able to constrain the density dependence of this oxygen enrichment, but we can place limits on the density range in which it resides. Hence, we introduce a new parameter: a gas overdensity threshold, $(\rho/\bar{\rho})_{\text{cut}}$. Where $\rho/\bar{\rho} < (\rho/\bar{\rho})_{\text{cut}}$, we add no oxygen, and where $\rho/\bar{\rho} > (\rho/\bar{\rho})_{\text{cut}}$ we add the constant $[O/H]$ specified. Figure 7 shows a likelihood plot of the fit to the SDSS data set for 208 models (with two parameters and nine data points). Where $(\rho/\bar{\rho})_{\text{cut}} = 0$, no threshold is used and the models correspond to those used in Figure 6. There is little or no change in the quality of the fit going from $(\rho/\bar{\rho})_{\text{cut}} = 0$ to $(\rho/\bar{\rho})_{\text{cut}} = 1$, and this indicates that our LCP search for O vii in the SDSS QSO sample is not sensitive to metals in underdense regions of the universe.

As the threshold is raised in our models a degeneracy becomes apparent, as seen in Figure 7: removing metals from low-density regions requires one to add more metals to higher density regions to compensate, and it is still possible to obtain a good fit. This indicates that our search is rather insensitive to the density of the systems enriched. As expected, the tight relationship between $\tau_{1329}$ and overdensity seen in high-resolution spectra (Rauch et al. 1997; Croft et al. 1998; Weinberg et al. 1998) breaks down due to the moderate resolution of the SDSS sample. Dense systems can always produce a low apparent $\tau_{1329}$ by virtue of the instrumental broadening over multiple pixels, but the key question is to what extent those systems can reproduce the observed signal? The agreement begins to break down at $(\rho/\bar{\rho})_{\text{cut}} \approx 6$, where we have 13% confidence (1.5$\sigma$) in our fit to the observed result, and it breaks down completely at $(\rho/\bar{\rho})_{\text{cut}} \approx 8.5$, where we have 5% confidence (2$\sigma$) in our fit. This breakdown occurs because there are proportionately too few higher density systems to obtain a fit to the search curve even with arbitrarily high metallicity. The best fit is obtained with $(\rho/\bar{\rho})_{\text{cut}} = 4$, where the fit has $\chi^2 = 9.4$ (23% confidence for two parameters and nine data points).

While Figure 7 shows that a range of two-parameter models can fit the data, we will show in Section 5 that the mass-weighted mean oxygen abundance is well constrained. To demonstrate this, we must first address the issue of scatter in the metallicity.

4.4. Scatter in the Metallicity

Schaye et al. (2003) (hereafter S03) and A08 found that a log-normal scatter in the metallicity is a good fit to all percentiles in their search. We assume the same scatter in order to have a better understanding of the nature of our search results. In particular, it is not clear if an $[O/H]$ model without scatter that fits the data gives a measure of the mean or median metallicity in the IGM.

A model with log-normal metallicity scatter, i.e., Gaussian scatter with variance $\sigma_y^2$ in $\log Z = [O/H]$, has

$$\log Z_{\text{med}} = \text{median}(\log Z) = \langle \log Z \rangle$$

$$= \log(Z) - \frac{\ln 10}{2} \sigma_y^2,$$  \hspace{1cm} (5)

where $\log Z_{\text{med}}$ and $\langle Z \rangle$ are the median and mean metallicity, respectively, and we adopt $\sigma_y^2 = 0.5$ (Schaye et al. 2003, Equation (7)). The log-normal scatter is added on scales of $1.2 h^{-1}$ Mpc comoving in regions where $-0.5 < \log(\rho/\bar{\rho}) < 2$. As Equation (5) shows, log-normal models with different scatter, $\sigma_y$, have the same $\langle \log Z \rangle$ and the same $Z_{\text{med}}$ but different $\langle Z \rangle$.

In order to test whether the LCP search for O vi is sensitive to the mean or median oxygen abundance we explore both interpretations.
models with scatter, one that has the same $⟨Z⟩$ and one that has the same $Z_{\text{med}}$. The good agreement in the former case indicates that our search for O vi is sensitive to the $⟨Z⟩$ or the mean O/H. Furthermore, we have tested this hypothesis using the A08 density-dependent fit to O vi seen in high-resolution spectra. They report a model fit,

$$[O/H] = [O/C] + [C/H]$$

$$= -2.81^{+0.15}_{-0.14} + 0.08^{+0.09}_{-0.06}(z - 3) + 0.65\text{^{+0.10}_{-0.14}}(\log[\rho/\bar{\rho}] - 0.5),$$

that is derived from O vi correlated with C iv and C iv correlated with H i. This model is a three-parameter fit to the median [O/H]. Since it is fit to independent data we treat it as having 9 degrees of freedom here (equal to the number of data points). When we reproduce this model in our simulations including scatter and perform the LCP search, it provides a reasonable fit to the SDSS data (about 2σ). However, where we have simply added metals to our simulation at this median level without scatter our agreement is poor (reduced $\chi^2$ = 6). When we use the correction factor in Equation (5) and add metals at the mean level instead, we obtain a reasonable fit once more (at about 1.5σ confidence).

5. MEASURING THE MEAN OXYGEN ABUNDANCE AND THE COSMIC OXYGEN DENSITY

Sections 4.3 and 4.4 present a variety of models that are consistent with our LCP search results, despite differences in density dependence and scatter. We can ask whether these models have a common feature of oxygen abundance that is well determined by our data. To this end, we have calculated the volume-weighted and mass-weighted means of O/H for all models that fit the data: those within 1.5σ and 2σ contours, along with the A08 model. Specifically, we compute the means by summing O/H (not [O/H]) over all pixels in the simulated spectra with mass density in the range $-0.5 < \log[\rho/\bar{\rho}] < 2$, either weighting each pixel equally (volume-weighted) or weighting in proportion to mass density.

The mass-weighted mean oxygen abundance, $[[O/H]_{\text{MW}}]$, for the “ridge line” of best-fitting models at every $(\rho/\bar{\rho})_{\text{cal}}$ is shown in Table 1. We list the models without scatter, but models with scatter yield the same results since (as shown in Figure 8) they must have the same mean oxygen abundance to fit the data. Taking models within the 1.5 and 2σ contours (rather than just this ridge line) provides a measure of both uncertainty in density dependence and observational uncertainty.

While the volume-weighted abundances span 0.4–1.3 dex in [O/H], the successful models all have mass-weighted means in the range $-2.51 < ([O/H]_{\text{MW}}) < -2.39$ (1.5σ) and $-2.56 < ([O/H]_{\text{MW}}) < -2.10$ (2σ). We conclude that the LCP measurements constrain the mass-weighted mean oxygen abundance of the IGM to be $([O/H]_{\text{MW}}) = -2.45 \pm 0.06$ (1.5σ) and $([O/H]_{\text{MW}}) = -2.33 \pm 0.23$ (2σ). We can compare this result directly with the mass-weighted mean in A08 of $([O/H]_{\text{MW}}) = -2.14 \pm 0.14$ (1σ), which is marginally consistent with our results. The volume-weighted mean oxygen abundance is more weakly constrained to $([O/H]_{\text{VW}}) = -3.06 \pm 0.22$ (1.5σ) and $([O/H]_{\text{VW}}) = -2.74 \pm 0.64$ (2σ). These error estimates do not include systematic uncertainties associated with the shape and intensity of the ionizing background (see Section 6.1) or uncertainties in the solar oxygen abundance. Using Caffau et al. (2008) values for the solar abundance of oxygen would give a mass-weighted $([O/H]_{\text{MW}}) = -2.34 \pm 0.06$ (1.5σ) and $([O/H]_{\text{MW}}) = -2.22 \pm 0.03$ (2σ).

With this measure of $([O/H]_{\text{MW}})$, and extrapolating to all densities, we can calculate the cosmic oxygen density using

$$\Omega_{\text{OXY, IGM}} \approx Y_H A_0 \Omega_b 10^{([O/H]_{\text{MW}})} (O/H)_0. \quad (7)$$

where $Y_H = 0.76$ is the mass fraction of hydrogen and $A_0 = 16$ is the atomic mass of oxygen. We obtain a value of $\Omega_{\text{OXY, IGM}} = 1.4(\pm0.2) \times 10^{-6}$ (1.5σ). This would be 5% smaller if we limited ourselves to the density range $-0.5 < \log[\rho/\bar{\rho}] < 2$ (the range for which the mass-weighted mean was calculated). This shows that the calculation is not sensitive to the details of the density range integrated over, but this is not a statement about the metal enrichment of systems beyond our constraining density range. In particular, the population of strong absorbers, such as those resulting in the $\tau_{\text{lya}} \approx 3.3$ point of our LCP, is better dealt with in directed searches (Frank et al. 2010a, 2010b).

If we follow the procedure of Bouché et al. (2007) (and A08) and take $\Omega_{Z, \text{IGM}} \approx \Omega_{\text{OXY, IGM}}/0.6$, then we obtain a total cosmic
metal density of the IGM, \( \Omega_{Z, IGM} \approx 2.3 \times 10^{-6} \). This is \( \approx 16\% \) of their metal budget of \( \Omega_{Z} = 1.5 \times 10^{-5} \) at \( z = 3 \) (from their Figure 1 and based on integrated cosmic star formation with standard assumptions about stellar initial mass function and yields). This metal content is over half that found in galaxies at \( z = 2.5 \) \( (30\%) \) while sub-DLAs may contribute between \( 2\% \) and \( 17\% \) (Bouché et al. 2007). Summing these values would account for over half of the metals produced by star formation. The remainder could plausibly reside in intermediate densities (e.g., strong O\textsc{vi} absorbers; Frank et al. 2010b) or in a hidden warm-hot phase, but uncertainties in the calculated metal production and the observational estimates preclude strong statements about “missing” metals.

6. DISCUSSION

6.1. Ionization Corrections

We have obtained the most precise constraints to date on the mass-weighted mean O/H and \( \Omega_{O_{2Y}} \), but our analysis rests on the assumption that the detected O\textsc{vi} is mostly ionized by a UV background with the spectral shape of the HM01 QG model. The use of this UV background model is motivated by the work of S03 and A08. They also use two other background models: one resulting from quasars only (“Q”) and a softened version of the QG model (“QGS”) with a lower flux above 4 ryd. They find that those two models are inconsistent with their relative abundance measures of [O/C] and [O/Si], while they obtain a good fit using the QG model. It is not clear to what extent small variations in the QG model can be tolerated, and what impact these would have on the quoted results. This is clearly an area that requires further investigation.

Our simulations assume a power-law equation of state and so underproduce gas at \( T > 10^5 \) K, which is dominated by collisional ionization. This choice is justified in light of studies by Carswell et al. (2002), Bergeron et al. (2002), and Simcoe et al. (2004) who show that O\textsc{vi} lines are typically too narrow to be in this phase. It is also notable that O\textsc{vi} which arises from collisional ionization also tends to be strong due to the high O\textsc{vi} fraction in this regime, while the O\textsc{vi} absorption probed here is relatively weak (even compared to the studies listed above).

A08 find a substantial increase in [O/H], for a fixed [O/C] ratio, for systems that have \( \rho/\bar{\rho} > 30 \). Lower densities are well described by photoionization and a fixed [O/C] ratio in their models. They conclude that \( \rho/\bar{\rho} > 30 \) regions are in fact collisionally ionized (while systems with \( \rho/\bar{\rho} < 30 \) are photoionized). Simcoe et al. (2004) also find such a change in [O/C] and infer a change in ionization mechanism at higher densities. We find indications of the same effect for our measure at \( \tau_{Ly\alpha} \approx 3.3 \), which shows O\textsc{vi} absorption at a level far higher than for lower \( \tau_{Ly\alpha} \). We have omitted this data point for our photoionization dominated analysis. We have only one point showing this effect, since we do not use higher order Lyman lines in our analysis and are therefore unable to cleanly isolate the highest density regions. We find a good fit at all detectable Ly\( \alpha \) absorption levels below \( \tau_{Ly\alpha} \approx 3.3 \) using a constant [O/H] and assuming a photoionized medium.

One should note that A08 normalize their UV background to a level that differs from ours. This leads to an adjustment on the ionization correction. The ratio of optical depths is related to the metallicity by

\[
\log \frac{\tau_{O\textsc{vi}}}{\tau_{Ly\alpha}} = \log \left( \frac{n_{O\textsc{vi}}}{n_{O}} \right) \left( \frac{n_{H}}{n_{H1}} \right) + [O/H] + \log(\Omega/H) + S, \tag{8}
\]

\[\text{Figure 9.} \quad \text{Ionization correction parameter (}\log(n_{O\textsc{vi}})/n_{O})\text{ in terms of the UV background intensity (normalized to the HM01 level) and ionization rate at } z = 3. \text{ This is calculated for three densities that span our range of sensitivity: mean density (solid line), log}(\rho/\bar{\rho}) = 0.5 \text{ (dotted line), and log}(\rho/\bar{\rho}) = 1 \text{ (dashed line). The thin vertical lines show the UVB intensity used in A08 and here.}
\]

where \( S = \log((f_\lambda)_{O\textsc{vi}}/(f_\lambda)_{Ly\alpha}) \). The first term on the right-hand side of this equation is the ionization correction term, and this is plotted against UV background intensity (normalized to the HM01 level) and the ionization rate in Figure 9. This was calculated assuming the equation of state in Equation (3) and \( z = 3 \) for three overdensities: log\( (\rho/\bar{\rho}) = 0.5, 0.5 \), and 1 that span our sensitivity range. Our chosen UV background intensity of \( 1.35 \times \text{HM01} \) (\( \Gamma = 13 \times 10^{-13} \text{ s}^{-1} \)) is shown along with the A08 value of \( 0.48 \times \text{HM01} \) (\( \Gamma = 4.6 \times 10^{-13} \text{ s}^{-1} \)). For mean density the ionization correction is largely unchanged between our simulations and those of A08; however, our models would result in systematically lower [O/H] resulting from oxygen in systems of log\( (\rho/\bar{\rho}) > 0.5 \) by between 0.3 and 1.1 dex. This might go some way to explaining the 0.2 dex lower value we find for [O/H]. Another source of potential discrepancy is differences in the density distributions between the studies. Despite these issues, we are in broad agreement with a metal budget fraction of \( \sim 15\% - 35\% \) in A08 for \( z = 2 - 3 \).

The success of the LCP search method for detection of O\textsc{vi} in the SDSS spectra may indicate that it is appealing for other searches for low level absorption in the IGM, where large numbers of moderate resolution spectra with moderate signal to noise and a substantial uncertainty in the continuum are available. There are a number of other species that may be detectable in the SDSS sample with a similar approach. Correlation searches in spectra from other instruments such as the Cosmic Origins Spectrograph, the Far-Ultraviolet Spectroscopic Explorer (FUSE), and the Space Telescope Imaging Spectrograph, or even the High Resolution Echelle Spectrometer and the Ultraviolet Visual Echelle Spectrograph, may benefit from this kind of analysis, which is resistant to errors in the continuum. Modulation of the number of local pixels used may also be a useful approach to measuring clustering of absorbers.

6.2. Continuum Correction Uncertainty

We systematically underestimate our continuum fitting such that the continua must be corrected up (and the transmitted flux down) by 16\% to match the mean flux measured in studies using high-resolution spectra. The uncertainty in those measurements may lead to systematic errors in our measurements. We use \( (F) = 0.68 \pm 0.04 \) at \( z = 3 \) from McDonald et al. (2000) and
these 1σ error estimates correspond to allowed corrections of 11%–25%. This would lead to a 15% offset in \( \langle \tau_{Ly\alpha} \rangle \), which would be corrected by a 15% offset in the recombination rate. This change in recombination rate results in a change to the \( H_1 \) fraction which is independent of density for the regime probed here, leaving the \( Ly\alpha \) forest largely unchanged. There is a small distortion due to the fact that an error which is a multiple in flux would be corrected by a factor which is a multiple in optical depth, but crucially most of the signal in the LCP search comes from higher optical depths for which the correction is even smaller. Also large errors of this sort would be evident in the comparison between the PDF of the flux in the simulations and the data in Figure 4.

A systematic error in the chosen \( \Gamma \) (based on an error in the mean flux in the literature) would also impact the \( O\, vi \) fraction. This error corresponds to half a minor tick interval in the upper horizontal axis of Figure 9 and so the ionization correction parameter would be largely unchanged over the density range of interest. One can conclude that in the context of (related) uncertainties in the shape and amplitude of the UV background, and so \( \Gamma \), these issues are a sub-dominant systematic uncertainty.

### 6.3. Other Searches for \( O\, vi \) in the IGM

Fox et al. (2008) argued that the lack of velocity dependence in the column densities (\( N \)) of their proximate (\( \delta v < 8000 \text{ km} \text{s}^{-1} \)) from \( \zeta_{\text{QSO}} \) sample indicates that their 26 weak \( O\, vi \) absorbers must be collisionally ionized. The majority of these absorbers likely correspond to systems of \( \rho/\bar{\rho} > 10 \) based on their associated \( H_1 \) column densities and using the \( N/\rho \) relation from Schaye (2001). Hence, they are sampling predominantly stronger absorbers than those considered here, so this work is not at odds with our choice of a photoionization model for our calculation of \( [O/\text{H}] \).

Our results appear consistent with other comparable measures of \( [O/\text{H}] \) in the IGM given the differences of method and thus the systems sampled. Carswell et al. (2002) also use high-resolution spectra to search for \( O\, vi \), but unlike Aguirre et al. (2008) they use Voigt profile fitting of detected lines. They argue that these lines at \( z = 2 \) are photoionized (and so are comparable with those we find) with abundances \( 10^{-3}–10^{-2} \) of solar.

Telfer et al. (2002) use stacked \( O\, v \) in \textit{FUSE} spectra to determine \( [O/\text{H}] \) and obtain a range of \(-2.2\) to \(-1.3\). Their higher value is partly caused by a combination of their use of a “Q” UV background model and by their lower redshift range (\( 1.6 < z < 2.9 \)). The main cause for the discrepancy is likely their use of the 78th percentile of their stack (in order to maximize signal-to-noise), while we use the 50th. Aguirre et al. (2008) argue that this difference likely corresponds to a 0.5 dex adjustment, bringing the results of Telfer et al. (2002) broadly into line with ours.

Bergeron & Herbert-Fort (2005) search for \( O\, vi \) lines at somewhat lower redshift range (\( 2 < z < 2.6 \)) than ours. They divide these lines as “metal-poor” and “metal-rich.” This differs greatly from our analysis and so is difficult to compare. In particular, they find the \( [O/\text{H}] \) of systems with detected \( O\, vi \) absorption while we calculate the average metallicity over all \( Ly\alpha \) absorption. Their “metal-poor” sample shows \(-3 < [O/\text{H}] < -1 \) and a cosmic oxygen density \( \Omega_{\text{O}_2} \approx 2.3 \pm 0.2 \times 10^{-6} \) using a photoionization model similar to the “Q” model described above, which is consistent with our results, but the numbers are not directly comparable.

Frank et al. (2010a) have searched the same SDSS data set with the goal of identifying strong \( O\, vi \) absorbers, requiring additionally associated \( Ly\alpha \) and \( Ly\beta \) absorption. The approach used is complementary to this work, as they can only retrieve strong absorbers that are typically saturated in both these Lyman lines. Hence, these absorbers are a different population from the ones probed here with higher density and (perhaps) collisional ionization. Frank et al. (2010b) provide a measure of the cosmic oxygen density contributed by these systems of \( \Omega_{\text{O}_2} \approx 1.9 \times 10^{-6} \text{h}^{-1} \) (which corresponds to a firm lower limit of \( \Omega_{\text{O}_2} \approx 1 \times 10^{-7} \text{h}^{-1} \) assuming the maximum \( O\, vi \) ionization fraction of 20%) at absorber redshifts \( 2.8 \leq z_{\text{abs}} \leq 3.2 \).

Our measure of the fraction of the estimated metal budget detected at \( z = 3 \) is in line with values calculated by Bouché et al. (2007) using results from various papers and various metals. They infer a “forest” contribution of \(<15\% \) at \( z = 2 \). One study they quote is particularly notable: Simcoe et al. (2004) find \( \Omega_{\text{O}_2} \approx 2 \times 10^{-6} \) using a “hard” (“Q” like) UV background. Bouché et al. (2007) re-analyze these results in the context of a “softer” (“QG” like) UV background model and find \( \Omega_{\text{O}_2} \approx 5 \times 10^{-6} \) at \( z = 2.5 \), and so a fraction of the metal budget of \( \approx 30\% \). This measure is consistent with our findings given redshift evolution and systematic uncertainties associated with search methods and ionization corrections. Simcoe et al. (2004) find a mean \( [O/\text{H}] = -2.85 \) for their lines (which is effectively a volume-weighted mean) for the 70% of systems in which they detected oxygen, which is also consistent with our findings (setting the other 30% to zero metallicity would result in a volume-weighted mean of \( [\langle O/\text{H}\rangle_{\text{VW}} = -3.00 \)).

### 7. CONCLUSIONS

We have developed a new method to detect \( O\, vi \) absorption in low-density regions with a data set that might initially seem ill suited to this purpose: the moderate resolution (\( R = 1800 \)), moderate S/N SDSS spectra of high-redshift QSOs. Not only have we successfully detected \( O\, vi \) with high significance (the null case is ruled out with reduced \( \chi^2 = 10 \)), but we have placed tighter limits on the mass-weighted mean oxygen abundance of low-density regions than ever before. The success of this method hinges on the sheer size of the SDSS sample of spectra and the use of local, uncorrelated pixels near the \( O\, vi \) absorber as a way of characterizing both the continuum-fitting error and the degree of contaminating absorption. This LCP search for \( O\, vi \) seen in SDSS DR3 is the main result of the paper, and the high precision of this new tracer for metals in the IGM is clear. Modeling has been necessary to interpret these results and conclusions about oxygen abundance the lognormal random fields have been used to produce more than 4.5 million synthetic spectra.

Our search at \( 2.7 < z < 3.2 \) is not sensitive to the density dependence of the \( [O/\text{H}] \) because of spectral resolution constraints, but using detailed modeling we are able to measure the oxygen abundance IGM densities of \( 1 \lesssim \rho/\bar{\rho} \lesssim 9 \) and can conclude the following.

1. A model with constant \( [O/\text{H}] = -2.15^{+0.07}_{-0.09} \) provides an adequate fit to the data (at the 2σ level), but a fit can also be obtained by removing metals from lower density regions and elevating the metallicity in regions enriched.
2. The addition of log-normal metallicity scatter leaves the quality of fit of these models largely unchanged, where the scatter-free model is treated as a measure of the mean \( O/\text{H} \) (or \( \log Z \)) and not the mean \( [O/\text{H}] \) (or \( \log Z \)).
3. The mass-weighted mean oxygen abundance is nearly constant among our viable models. As a result, we have been able to place the tightest constraints thus far on
this quantity, \([\mathrm{O/H}]_{\text{MW}} = -2.45 \pm 0.06\) (at 1.5\(\sigma\) confidence) computed over the density range \(-0.5 < \log(\rho/\bar{\rho}) < 2\). This value is based on a Grevesse et al. (1996) solar abundance of oxygen. A Caffau et al. (2008) solar abundance would give a abundance \([\mathrm{O/H}]_{\text{MW}} = -2.34 \pm 0.06\).

4. The models that fit the data have volume-weighted mean, \([\mathrm{O/H}]_{\text{MW}} = -3.01 \pm 0.33\) (at 1.5\(\sigma\) confidence).

5. We calculate the cosmic density of oxygen, \(\Omega_{\text{O}_2}\) = 1.4(\pm 0.2) \times 10^{-6}. In the context of the work by Bouché et al. (2007), this constitutes a total metal contribution of \(\Omega_{\text{Z}\text{IGM}} \approx 2.3 \times 10^{-6}\), which is \(\approx 16\%\) of their estimated metal budget at \(z = 3\).

This novel LCP method need not be limited to the search for metals in the IGM. It could be adapted to spectral searches wherever bulk, low-level correlated absorption is expected and continuum errors and contaminating absorbers are the limiting factors. Little prior knowledge of these errors and uncertainties is required, only that they are uncorrelated.

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