THE PROPERTIES OF INTERGALACTIC C IV AND Si IV ABSORPTION. I. OPTIMAL ANALYSIS OF AN EXTREMELY HIGH SIGNAL-TO-NOISE QUASAR SAMPLE

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ABSTRACT

We have analyzed the properties of metals in the high-redshift intergalactic medium using a novel objective pixel optical depth technique on a sample of extremely high signal-to-noise ratio Keck HIRES and ESI spectra of 26 quasars between redshifts 2.1 and 6.4. The technique relies on using the doublet nature of the common ions C IV and Si IV, which are the principal metal tracers in the intergalactic medium outside of the Ly\(\alpha\) forest. Optical depths are statistically corrected for contamination by other lines, telluric absorption, bad pixels, continuum fitting, etc. and for incompleteness, and we achieve in this way an increased sensitivity of approximately 0.5 dex over previous analyses. As with existing pixel optical depth analyses, the method is completely objective and avoids subjective cloud selection and Voigt profile fitting, but, unlike existing techniques, we do not compare the ion optical depths with H I optical depths to determine the ion optical depth distributions; we therefore avoid problems arising from different velocity widths in the ion and H I. We have shown how the conventional analysis can be reproduced using a percolation method to generate pseudoclouds from ion optical depths. Using this set of pseudoclouds, we have generated C IV column density distributions and have confirmed that the shape of the C IV column density distribution remains essentially invariant, with slope \(-1.44\), from \(z = 1.5\) to 5.5. This in turn confirms the lack of redshift evolution of \(\Omega(C IV)\) for \(z = 2\)–5, both for all absorbers with column density \(N = 12\)–15 and for stronger absorbers with \(N = 13\)–14.

The generation of pseudoclouds from the optical depth vectors also gives information on the column density environment of a given optical depth. We find that for the higher resolution HIRES data there is a tight relation, \(\tau \sim N^{0.7}\), between the peak optical depth and the column density. We have then analyzed the ion redshift evolution directly and model-independently from the optical depth vectors themselves and show that there is little evolution in the total amount of C IV from \(z = 2\) to 5, although there is a turnaround of at least a factor of 2 in \(\Omega(C IV)\) above \(z = 5\). We do, however, see substantial evolution in the ratio Si IV/C IV. In two subsequent papers in this series, we will use this technique to investigate what fraction of the absorbers lie in galactic wind outflows (Paper II) and what metallicity is associated with regions of \(\tau(Ly\alpha) < 1\) (Paper III).

Key words: early universe — galaxies: formation — intergalactic medium — quasars: absorption lines

1. INTRODUCTION

The availability of very efficient high-resolution spectrographs on 8–10 m class telescopes (Vogt et al. 1994; D’Odorico et al. 2000) provided the very high signal-to-noise ratio (S/N) observations of high-redshift quasars needed to confirm earlier suggestions (e.g., Meyer & York 1987) that many of the stronger lines seen in the Ly\(\alpha\) forest of quasar spectra have associated metal absorption lines (Cowie et al. 1995; Tytler et al. 1995). Over the past few years these metal features have been extensively studied using Voigt profile fitting (e.g., Songaila & Cowie 1996; Songaila 1998, 2001; Ellison et al. 2000; Pichon et al. 2003; Simcoe et al. 2004; Aracil et al. 2004) and the so-called pixel optical depth (POD) methods in which the metal-line optical depths are cross-correlated with neutral hydrogen absorption (Cowie & Songaila 1998; Songaila 1998; Aguirre et al. 2002, 2004; Schaye et al. 2003). Down to the sensitivity limit of these methods \([\tau(Ly\alpha) \sim 1]\), metal enrichment seems ubiquitous, with a median value of \([C/H] = -3.47\) at an overdensity of \(10^{0.5}\), although there is a considerable spread of nearly a dex in the metallicity at every overdensity and an equally significant trend with overdensity (Schaye et al. 2003). It also appears that there is very little change in the distribution of C IV absorbers over a very wide redshift range (Songaila 2001).

The origin of these metals is still unclear; some may be in the process of being injected into the intergalactic medium (IGM) from galaxies at the redshifts in question (we refer to this as contemporary injection; Adelberger et al. 2003; Pettini et al. 2000, 2003), whereas others may have been put in place by earlier galaxy formation or by generations of Population III stars (Wassberg & Qian 2000; Madau et al. 2001; Qian et al. 2002; Bromm et al. 2003; Venkatesan & Truran 2003; Mackey et al. 2003; Fujita et al. 2004; Daigne et al. 2004; Yoshida et al. 2004). It is very likely that both processes contribute, and one of the primary goals of the present series of papers is to see whether we can distinguish among systems formed by the various processes and determine whether or not the enrichment mechanism relates to intrinsic properties of the metal systems, such as their column density, velocity structure, or redshift.

An essential prerequisite of these analyses is, however, the existence of extremely high S/N observations of the quasars. Over the past few years we have been obtaining very long exposure spectra of the brightest quasars accessible with the HIRES spectrograph and the Echellette Spectrograph and Imager (ESI) on the Keck 10 m telescope. In this set of papers we describe these observations and then use them to reanalyze the properties of the forest metals. In this first paper we describe a more objective technique for analyzing the spectra that allows us to make a deeper analysis of the data than is possible with Voigt profile fitting. In two subsequent papers we will use this method to address two of the outstanding problems associated with IGM

1 Visiting Astronomer, W. M. Keck Observatory, which is jointly operated by the California Institute of Technology and the University of California.
metal-enrichment scenarios, namely, what fraction of the absorbers lie in galactic wind outflows (Paper II) and what metallicity is associated with regions of Ly$\alpha$ optical depth $\tau$(Ly$\alpha$) < 1 (Paper III).

Voigt profile fitting is an inherently subjective procedure, both in the initial visual selection of the line candidates and also in the choice of cloud model to fit the line. The errors and incompleteness are therefore hard to quantify. The current POD methods, while extremely sensitive and objectively quantifiable, are sensitive only to metal lines with other counterparts, either other metal lines or, more usually, strong hydrogen lines, and also suffer in those cases in which the velocity structure of the metal lines differs markedly from that of the counterpart line. Therefore, we need a new technique to analyze the absorption structure that allows us to objectively analyze the metal data alone and to probe to the deepest possible levels that the data allow. In this paper we develop a new method that relies only on the doublet itself.

The primary metal-absorption features outside of the H I forest in high-redshift quasar spectra are C iv and Si iv lines, and the fact that these are doublets and nearly all unsaturated lines suggests an approach to this problem. In this paper we describe a POD technique in which we analyze the spectra by looking for regions where the optical depths at the relative wavelengths of the doublet approximate the expected 2 : 1 ratio; we call this the superposed POD, or “superPOD,” method. We show (§ 3) how incompleteness of the selection arising from noise and line overlap can be quantified and how the completeness correction can be modeled by adding artificial lines to the spectra. The overall analysis, which parallels the methods used to generate number counts in images, allows us to probe a factor of about 0.5 dex deeper in the absorption-line structure than the conventional techniques. However, even more importantly, the method is fully automatic, and therefore biases and incompleteness can be handled properly. We also show (§ 4) how the conventional analysis can be reproduced by a percolation analysis of the optical depth results. Finally (§ 5), we use the data to reanalyze the evolution of the absorption with redshift and confirm the result that there is little evolution of the distribution of the C iv absorbers over the $z = 2$–5 redshift range. We assume throughout a standard ΛCDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 65$ km s$^{-1}$.

2. OBSERVATIONS

The quasar observations are summarized in Table 1. All the $z < 4$ quasars were observed with the HIRES spectrograph on the Keck I 10 m telescope (Vogt et al. 1994) using the red cross-disperser. Nearly all of the observations were taken prior to the replacement of the HIRES CCDs in 2004 but after the installation of the rotator, which allowed the observations to be made at the parallactic angle. A 1′′1 slit width was used, giving a measured resolution of 39,000. Multiple spectrograph settings were used to give complete wavelength coverage, and observations spread over a number of years, from the first use of HIRES in 1994 to the present, were combined to give the final spectra. The $z > 4$ quasars were observed with the lower resolution ESI (Sheinis et al. 2000) on the Keck II 10 m telescope. The slit width of 0′′75 gives a resolution of $\sim$5300.

All the reductions were carried out using an IDL software package written by the author. More details can be found in

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| Quasar       | $z_{em}$ | S/N 1250 Å | S/N 1400 Å | Instrument | Sample |
|--------------|----------|------------|------------|------------|--------|
| SDSS 1148+52 | 6.39000  | 80         | –5         | E          | …      |
| SDSS 1048+46 | 6.23000  | 75         | –5         | E          | …      |
| SDSS 1306+03 | 5.98500  | 95         | –5         | E          | 4      |
| SDSS 0836+00 | 5.76500  | 130        | 55         | E          | 4      |
| SDSS 1044–01 | 5.75500  | 70         | 25         | E          | 4      |
| SDSS 1204–00 | 5.05500  | 105        | 80         | E          | 4      |
| SDSS 0338+00 | 4.99000  | 115        | 45         | E          | 4      |
| SDSS 1737+58 | 4.84000  | 100        | 115        | E          | 3, 4   |
| SDSS 2200+00 | 4.76300  | 125        | 65         | E          | 3, 4   |
| BR 1202–0725 | 4.60000  | 135        | 95         | E          | 3      |
| BR 0334–1612 | 4.36000  | 130        | 85         | E          | 3      |
| BR 0353–3820 | 4.55500  | 100        | 60         | E          | 3      |
| BR 2237–0607 | 4.55000  | 230        | 220        | E          | 3      |
| PSS 0747+443 | 4.43200  | 95         | 60         | E          | 3      |
| BRI 0952–011 | 4.40800  | 100        | 90         | E          | 3      |
| PSS 0926+305 | 4.19000  | 135        | 120        | E          | 3      |
| BR 2237–0607 | 4.55000  | 55         | 35         | HH         | …      |
| Q1422+2309   | 3.62000  | 340        | 285        | H          | H, 2   |
| HS 0741+4741 | 3.22000  | 210        | 185        | H          | H, 2   |
| Q0636+680    | 3.18000  | 220        | 165        | H          | H, 2   |
| HS 1946+7658 | 3.03000  | 210        | 200        | H, HH      | H, 2   |
| HS 0741+4741 | 3.22000  | 210        | 185        | H          | H, 2   |
| Q0636+680    | 3.18000  | 220        | 165        | H          | H, 2   |
| HE 2347–4342 | 2.88000  | 115        | 105        | H          | 1      |
| HS 0119+1432 | 2.87000  | 115        | 95         | H          | 1      |
| HS 1700+6416 | 2.72000  | 205        | 175        | H          | H, 1   |
| HE 1122–1648 | 2.40000  | 60         | 75         | H          | 1      |
| HS 1626+6433 | 2.31000  | 55         | 80         | H          | 1      |
| Q1331+170    | 2.08000  | 30         | 110        | H          | 1      |

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a: E: ESI spectrograph on the Keck II telescope; H: HIRES spectrograph on the Keck I telescope; HH: HIRES with upgraded detector.
b: H: High S/N sample; 1, 2, 3, and 4: Samples with $\langle z \rangle = 2.2, 2.8, 3.9, \text{and } 4.5$, respectively.
Songaila (2001; ESI) and Songaila (1998; HIRES). The individual spectra and associated noise and sky files can be found on the World Wide Web. In each case we have quantified the quality of the spectrum by the S/N measured in a velocity interval of 20 km s$^{-1}$ at two rest wavelengths (1250 and 1400 Å) in the quasar frame. The final S/N values measured in each of the spectra are shown in Table 1. The five spectra with the highest quality S/N values near or above 200 in this interval and are marked with an H in the table. We refer to this as the core quasar sample. These quasars have emission redshifts from 2.72 to 3.62.

3. ANALYSIS METHOD

We restrict our analysis to absorption lines that lie more than 1000 km s$^{-1}$ longward of the quasar’s Ly$\alpha$ emission and whose redshift is more than 4000 km s$^{-1}$ blueward of the quasar redshift; this avoids contamination by the Ly$\alpha$ forest and any absorption associated with the quasar itself. The continuum was locally fit with a seventh-order polynomial, iterating to remove absorption features, and the optical depth versus wavelength was determined through the chosen wavelength region for each quasar. An upper limit of $\tau = 4.8$ was imposed where regions were saturated. The optical depth vectors were smoothed to prevent oversampling. A 5 km s$^{-1}$ boxcar smoothing was chosen, which roughly matches the half-widths of features seen in the metal forest. A sample region of an optical depth vector can be found in Figure 1.

The distribution of optical depths in the core quasar sample is shown in Figure 2. In the selected wavelength region, 3.4% of the pixels in the optical depth vectors in the core sample have optical depths above 0.1, and about one-third lie above 0.005. Much of this structure is produced by C iv, but there are also contributions from Si iv, N v, and lower ionization lines, as well as incompletely removed telluric features, continuum-fitting errors, etc. The total optical depth can be used to provide an upper estimate of $\Omega$(C iv). Features with $\tau > 0.005$ correspond to $\Omega$(C iv) $< 5.8 \times 10^{-8}$ in the five quasars of the core sample. Much of this comes from higher optical depth regions; $\tau > 0.1$ gives a contribution to this number of $4.6 \times 10^{-8}$. Portions of the spectrum with $0.01 < \tau < 0.1$ give $1.0 \times 10^{-8}$. As we subsequently show, slightly more than 50% of the total absorption comes from the C iv doublets.

The doublet structure of the C iv, Si iv, and N v lines can now be used to reduce the contamination by other lines or artifacts. For each wavelength position in the optical depth vector we can look at the corresponding wavelength position of the second member of the doublet and see if the optical depth is in the correct ratio of roughly 2 : 1. We can then restrict the optical depth vector to positions at which the condition is satisfied and set the remaining positions of the vector to zero. We refer to this final vector as the cleaned optical depth. In general, the measured doublet ratio will only approximate the true value because of noise, errors in the continuum fit, line contamination, etc., and we need to specify a selection parameter, that is, the range of acceptable ratios, which we refer to as the doublet ratio window.

Too wide a choice of window will result in overselection of false-positive signals, whereas too narrow a choice will eliminate too many real systems, especially at low optical depth. We have chosen a doublet ratio window of 1 : 1 to 4 : 1 in the present work. We discuss reasons for this choice below.

The procedure is illustrated in Figure 1. The bottom panel shows the C iv 1548 optical depth as a function of wavelength for a 50 Å sample of spectrum, with one strong C iv line. In the middle panel the C iv 1550 optical depth is shown in the rest frame of the C iv 1548 line. Both vectors are individually smoothed as previously described. Finally, in the top panel, the result of the optical depth selection criterion of $0.25 < \tau(1548)/\tau(1550) < 1$ is shown and confirms the strong system as a real C iv doublet while removing much of the weaker structure seen in the raw C iv 1548 optical depth vector.

Figure 3 shows the procedure in a different way. Here we have plotted on the x-axis the C iv 1548 optical depth over the wavelength range and on the y-axis the corresponding optical depth at the second member of the C iv doublet. We label these as $\tau(1548)$ and $\tau(1550)$, respectively. Features that correspond to

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2 See http://www.ifa.hawaii.edu/~acowie/spectra.html.
uncontaminated C\textsc{iv} absorption lie along the diagonal line, which is indeed seen to be heavily populated. The parallel lines show the C\textsc{iv} doublet ratio window, here set to 0.25–1. Clearly, a narrower window could be used at high optical depths, but since there is little contamination there is no necessity for this. At a lower optical depth a narrower window would result in a larger proportion of the points being scattered out of the window. In this figure, absorption features that are not C\textsc{iv} fall in the lower right corner if they lie at the 1548 Å position and in the upper left corner if they are at the 1550 Å position. It is these features that are cleaned from the sample by the doublet ratio selection. The final cleaned optical depth is $\tau(1548)$ for all objects that lie within the tram lines and zero for those outside.

A major advantage of this method is that it allows an objective analysis of the degree of contamination, since we can compare the optical depth distribution for a true doublet—C\textsc{iv}, for example—with a similarly generated optical depth distribution for artificial doublets with slightly different wavelength spacing. This is illustrated in Figure 4, where we show the plot of $\tau(artificial)$ versus $\tau(1548)$ for an artificial doublet with 12 Å spacing. There are only a small number of contaminating points within the tram lines. It is also visually obvious by comparing Figure 3 (the true doublets) with Figure 4 (the artificial doublets) that the signal of real doublets (the difference between the number of true and artificial positions) persists at least to $\tau(C\textsc{iv} \lambda 1548) \approx 0.01$. The aim of the method is to find a statistical measure of the signal down to the deepest possible level.

Since the noise levels vary from spectrum to spectrum, and since telluric contamination may be a function of the wavelength position, this type of analysis is best carried out individually on each quasar spectrum with the individual results subsequently being combined. Figure 5 shows the results for the $z_{em} = 3.03$ quasar HS 1946+7658, which has a S/N at the low end of the high-S/N quasar core sample. The solid histogram with ±1 σ error bars in Figure 5 is the C\textsc{iv} $\lambda 1548$ optical depth distribution for lines in the spectrum selected as previously discussed. The dashed histogram is the average optical depth distribution retrieved from 20 artificial doublets with incorrect doublet separations to model contamination of real C\textsc{iv} doublets by interloper lines, bad pixels, telluric absorption, etc.

The difference between the solid and dashed histograms of Figure 5, illustrating the C\textsc{iv} $\lambda 1548$ optical depth distribution statistically corrected for contamination. There is significant positive signal down to $\tau(1548) \approx 0.005$. 

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Fig. 3.—The 1550 Å optical depth vs. 1548 Å optical depth for all the measured optical depths in HS 1946+7658. The solid lines indicate the optical depth selection criteria of $0.25 < \tau(1548)/\tau(1550) < 1$. Detected C\textsc{iv} doublets are clearly present visually down to $\tau(1548) \sim 0.01$. Only positions with $\tau(1548) < 4$ are plotted. Saturated regions appear at $\tau = 4.8$ in the $\tau(1550)$ axis.

Fig. 4.—Same as Fig. 3, but for artificially generated false doublets with doublet separation of 12 Å.

Fig. 5.—Solid histogram: C\textsc{iv} $\lambda 1548$ optical depth distribution for selected lines in the spectrum of the $z_{em} = 3.03$ quasar HS 1946+7658. Error bars are ±1 σ. Lines were chosen as illustrated in Figs. 1 and 2. Dashed histogram: Average optical depth distribution retrieved from 20 artificial doublets with incorrect doublet separations to model contamination of real C\textsc{iv} doublets by interloper lines, bad pixels, telluric absorption, etc.

Fig. 6.—Difference between the solid and dashed histograms of Fig. 5, illustrating the C\textsc{iv} $\lambda 1548$ optical depth distribution statistically corrected for contamination. There is significant positive signal down to $\tau(1548) \approx 0.005$. 

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structure, telluric absorption, etc. The difference between the two histograms, shown in Figure 6, is the \( \text{Civ} \) optical depth distribution statistically corrected for contamination. There is significant positive signal down to at least \( \frac{1}{C_{24}} \cdot 0.005 \).

The distributions must also be corrected for incompleteness, since lines that are contaminated by other absorption features will be missed and noise and structure may scatter weak lines outside the selection window. That is, as well as knowing what the signal is, we also need to have an accurate estimate of the line recovery rate. We do this in standard fashion by introducing artificial lines into the real spectra and tracking the number of recoveries as a function of the \( \text{Civ} \) optical depth. The lines are added in a Monte Carlo fashion drawn from the observed core sample \( \text{Civ} \) distribution. The line widths are chosen to match the range seen in the observed absorption features, but the method is not particularly sensitive to this choice. Figure 7 shows a sample strip of spectrum into which two artificial doublets with column density \( \log N(\text{Civ}) = 11.75 \) and two with \( \log N(\text{Civ}) = 12.75 \) have been introduced. The panels have the same meaning as in Figure 1, and the short vertical lines in the top panel indicate the wavelengths of the introduced artificial lines.

![Fig. 7. Illustration of the method of measuring the recovery rate of artificial doublets. Two artificial \( \text{Civ} \) doublets with column density \( \log N(\text{Civ}) = 11.75 \) and two with \( \log N(\text{Civ}) = 12.75 \) have been inserted into the region of the spectrum of HS 1946+7658 shown in Fig. 1. The panels have the same meaning as in Fig. 1. Short vertical lines in the top panel show the wavelengths of the introduced artificial lines.](image)

The panels have the same meaning as in Figure 1, and the short vertical lines in the top panel indicate the wavelengths of the introduced lines. This is the line strength at which recovery starts to break down, going from 100\% at \( \log N(\text{Civ}) = 12 \) to 75\% at \( \log N(\text{Civ}) = 11 \). The recovery rate is also a function of the resolution of the spectra, and contamination is more severe and

![Fig. 8. Fraction of recovered pixels as a function of the input optical depth in the 1548 Å line for the five quasars in the core quasar sample. At higher optical depths the small incompleteness is primarily caused by line blending. The recovery begins to drop rapidly at lower optical depths because of noise scattering, which moves ratios outside the doublet window. The recovery in these quasars drops to 0.5 at \( \tau = 0.017 \) and to 0.25 at \( \tau = 0.007 \), at which point we consider we have reached the useful limit of the data.](image)

...in a Monte Carlo fashion drawn from the observed core sample \( \text{Civ} \) distribution. The line widths are chosen to match the range seen in the observed absorption features, but the method is not particularly sensitive to this choice. Figure 7 shows a sample strip of spectrum into which two artificial doublets with \( \log N(\text{Civ}) = 11.75 \) and two with \( \log N(\text{Civ}) = 12.75 \) have been introduced. The panels have the same meaning as in Figure 1, and the short vertical lines in the top panel indicate the wavelengths of the introduced lines. This is the line strength at which recovery starts to break down, going from 100\% at \( \log N(\text{Civ}) = 12 \) to 75\% at \( \log N(\text{Civ}) = 11 \). The recovery rate is also a function of the resolution of the spectra, and contamination is more severe and

![Fig. 9. Pseudocloud complexes in a region of the spectrum of the quasar Q1422+2309. Top: Cleared \( \text{Civ} \) optical depth vector. The analysis, with a 100 km s\(^{-1}\) cloud window, splits this region into two complexes that are marked by the horizontal solid lines. Bottom: Corresponding region of the \( \text{Ly} \) line, which shows that the complex breakdown matches well to the \( \text{Ly} \) structure. However, the exact breakdown is subject to the exact choice of window. A 150 km s\(^{-1}\) window would reduce this particular system to one complex, whereas a 50 km s\(^{-1}\) window would split it into three parts.](image)

![Fig. 10. Number of complexes retrieved in the core quasar sample as a function of column density for three velocity windows: 75 (triangles), 150 (squares), and 300 km s\(^{-1}\) (diamonds). The effect of widening the window is to blend weaker systems into larger complexes and so reduce the number of low column density systems; but, as can be seen from the figure, the effect is not large for reasonable values of the velocity window. The solid line indicates the number of systems found as a function of column density for a set of artificial doublets approximating the \( \text{Civ} \) separation; this shows the degree of contamination at a given column density.](image)
4. VOIGT PROFILE FITTING EMULATION

The cleaned optical depth vector contains all the information present in the traditional cloud analyses, and in general it is best to use this directly to analyze the absorption structure. However, it is interesting and very straightforward to relate the present type of analysis to the analysis by Voigt profile fitting and to see how well we reproduce the results previously obtained by this method. In addition, we can use the method to characterize the local environment in which a given optical depth point lies.

Recovery poorer in the lower resolution high-redshift ESI spectra. The final recovery rate versus optical depth is shown in Figure 8. This gives the incompleteness correction as a function of optical depth for the individual quasar spectrum, which can then be divided into the observed optical depth of Figure 6 to obtain the true optical depth distribution. For the high-S/N core quasar sample, incompleteness reaches 50% at an optical depth of \( \sim 0.017 \).

Fig. 11.—Open squares: \( C_\text{iv} \) column density distribution of pseudoclouds determined using a velocity window of 100 km s\(^{-1}\) (see text) from the \( C_\text{iv} \) optical depths retrieved by the superPOD method from the core quasar sample. The average \( C_\text{iv} \) redshift is 2.7. Filled squares: Distribution corrected for incompleteness with 1 \( \sigma \) error bars. Circles: Distribution obtained by Voigt profile fitting of \( C_\text{iv} \) doublets selected by hand from the spectra with no incompleteness correction. Dotted line: Fit to the data with power-law index \(-1.44\). Solid line: Power law slope \(-1.7\), which fits the \( N(C_\text{iv}) > 10^{13} \text{ cm}^{-2} \) sample.

Fig. 12.—Filled squares: \( \Sigma(C_\text{iv}) \) as a function of redshift computed from \( C_\text{iv} \) column density distributions of pseudoclouds with \( 12 < \log N(C_\text{iv}) < 15 \) obtained from \( C_\text{iv} \) optical depths retrieved by the superPOD method from various samples of quasars with \( 2 < z < 5.5 \). Open squares: Same as filled squares but with \( 13 < \log N(C_\text{iv}) < 14 \).

We can use the superPOD method to emulate the usual Voigt profile fitting analysis of the spectra in an objective way. The basis of this is to generate “pseudocloud complexes” by combining neighboring optical depths with detections into a single line profile. We do this by first finding the maximum optical depth in the true optical depth vector. We then define the cloud complex as all positions with nonzero optical depths that are connected to the primary position, with gaps where the optical depth is zero being less than 100 km s\(^{-1}\). An example of a complex picked out in this way is shown in Figure 9. Positions already allocated to cloud complexes are eliminated from the cleaned optical depth vector and the process repeated. The column density is computed for each cloud complex from the integral of the optical depths included in it, with each optical depth being weighted by the completeness and contamination correction for that optical depth.

The exact definition of “neighboring” is somewhat arbitrary in the use of the 100 km s\(^{-1}\) window to define the cloud size. In general, the wider the cloud window, the more likely one is to lose lower column density clouds as individual entities: they would be incorporated into broader cloud complexes. However,
in practice, for reasonable values of the window the results are not too sensitive to this choice. We illustrate this in Figure 10, where we show the number of clouds found as a function of column density for velocity windows of 75–300 km s\(^{-1}\). The wider window reduces the number of independent low column density complexes, but the effect is not large.

In Figure 11 we show as open squares the raw C\(\text{ iv}\) column density distribution of pseudoclouds obtained from C\(\text{ iv}\) optical depths retrieved by the superPOD method from the core quasar sample at an average redshift of 2.7. The filled squares with 1\(\sigma\) error bars show the distribution corrected for incompleteness and bias. For comparison, the open circles show the results of a traditional analysis of the same set of objects, conducted in the usual way with visual identification of lines and subsequent manual Voigt profile fitting. The best-fit line has a slope of \(-1.44\), similar to the result of Ellison et al. (2000) at the same redshift. This is shown by the dashed line in Figure 11. The solid line has a slope of \(-1.7\), based on fitting only to complexes with \(N(\text{C}\ iv) > 10^{13}\) cm\(^{-2}\).

Using the various quasar samples of Table 1 at low and high redshifts, we have constructed in this way the C\(\text{ iv}\) column density distributions in the redshift range 1.5–5.5. In general, the superPOD method using pseudocloud generation reproduces the invariance of the C\(\text{ iv}\) column density distribution function with redshifts already determined by traditional methods (Songaila 1997, 2001; Pettini et al. 2003), and, with an extra sensitivity of about 0.5 dex over these previous results, the redshift invariance of the distribution functions is seen very clearly. Following the methods used in the previous studies, we can also construct \(\Omega(\text{C}\ iv)\) as a function of redshift (Fig. 12). This agrees very well with the traditional studies in showing that \(\Omega(\text{C}\ iv)\) remains nearly invariant between redshifts 2 and 5. This remains true whether counting stronger absorbers (open squares; \(13 < \log N(\text{C}\ iv) < 14\)) or all absorbers (filled squares; \(12 < \log N(\text{C}\ iv) < 15\)).

We can extend the method by computing the column densities of lines corresponding to other species for the range of velocities in each C\(\text{ iv}\)–selected cloud complex. For doublets such as Si\(\text{ iv}\) we use the cleaned optical depth for that species, while for singlets such as C\(\text{ ii}\) we simply use the raw optical depth. These ion ratios are shown as a function of redshift for the stronger cloud complexes in Figures 13 and 14. In both figures, the filled squares denote the ion ratios determined from the C\(\text{ iv}\) pseudoclouds (with a width of 100 km s\(^{-1}\)), whereas the diamonds show the median

**Fig. 15.** K-S test of the hypothesis that the Si\(\text{ iv}/\text{C}\ iv\) ratio in the cloud complexes at \(3.5 < z < 4.5\) (dashed line) is the same as at \(2 < z < 3\) (solid line). The Si\(\text{ iv}/\text{C}\ iv\) ratios are significantly weighted to higher values at the higher redshifts, despite the fact that the distribution of C\(\text{ iv}\) column densities has not changed.

**Fig. 16.** Cleaned C\(\text{ iv}\)(1548) optical depths vs. the column density of the complex in which they lie. HIRES data are shown in (a) and ESI data in (b). For the HIRES data there is a tight relation, \(\tau \sim N^{0.7}\) (solid line), between the peak optical depth and the column density of the complex. This is not as apparent in the lower resolution ESI data.

**Fig. 17.** Squares: Average \(\Omega(\text{C}\ iv)\) as a function of redshift computed directly from C\(\text{ iv}\) optical depths retrieved by the superPOD method from various samples of quasars with \(2 < z < 5.5\). Redshift bins are \([1.5, 2.5], [2.5, 3.5], [3.5, 4.5], [4.5, 5.5]\), with the observation shown at the mean redshift in the interval. Diamonds: Same as squares, but for Si\(\text{ iv}\).
ion ratios in each redshift bin determined directly from the optical depths. Figure 13 demonstrates that neither the range nor the median value of C\textsubscript{i}i/C\textsubscript{iv} changes significantly as a function of redshift, agreeing with Schaye et al. (2003). However, the same is not true of Si\textsubscript{iv}/C\textsubscript{iv}, a result that a Kolmogorov-Smirnov (K-S) test (Fig. 15) shows to be highly significant. The open squares in Figure 14 denote pseudoclouds with high C\textsubscript{iv} column density. The K-S test is based on all the Si\textsubscript{iv} and C\textsubscript{iv} systems, including these strong ones. However, it is dominated by the larger numbers of smaller column density systems. On the other hand, evolution in both \Omega(C\textsubscript{iv}) and \Omega(Si\textsubscript{iv}) is dominated by the high column density end of the distribution. We discuss this further, using optical depth vectors, in Paper II, and we postpone the interpretation to that paper.

Fig. 18.—Total absorption (the sum of the optical depths) per unit x in optical depth bins of 0.1. Each panel contains five quasars ordered by redshift. The results in (a) and (b) are based on HIRES data, and those in (c), (d), and (e) are based on ESI data. The solid line indicates the distribution of the core sample. In (c), (d), and (e) this is smoothed to the ESI spectral resolution.
between the peak optical depth and the column density, which is washed out in the lower resolution ESI data. In Paper II we shall revisit this relation, which implies that higher column density clouds or, equivalently, systems with larger peak optical depths are also wider in velocity space.

5. OPTICAL DEPTH ANALYSIS

It is encouraging that there is such good agreement between traditional Voigt profile fitting methods and the objective, but still slightly arbitrary, method of generating pseudocloud complexes. However, the real merit of the superPOD technique lies in the fact that the cleaned optical depth vectors contain all the information about the amount of material, its distribution in strength, and the velocity structure of the absorption and may be used directly to characterize these without ever resorting to arbitrary groupings.

In the present paper we use the optical depth vectors to determine the metallicity evolution directly from C iv and Si iv optical depths, postponing a discussion of the velocity structure and the ionization balance evolution to Paper II. Our results are shown in Figure 17 for C iv (squares) and Si iv (diamonds) in four redshift bins: [1.5, 2.5], [2.5, 3.5], [3.5, 4.5], and [4.5, 5.5]. We see a factor of 2 turnaround in C iv at z = 5 and perhaps a larger turnaround in Si iv at the same redshift. The S/N of the data is declining at the highest redshifts and the sky systematics are higher, but, even given these caveats, the slight turnaround at these redshifts seems real and could correspond to a decline in the metal density or a change in the ionization balance (Schaye et al. 2003). Irrespective of this point, there is clearly a significant metal density in place at z = 5.

In Figure 18 we show the optical depth distributions of C iv over the same redshift ranges. We have divided the quasar sample into five sets of five quasars, ordered by redshift, which are shown in panels a–e. (We omitted the quasar PSS 0747+443 and divided the remainder to give the five groups.) The redshift range of C iv absorption in each set of quasars is marked in each panel.

The three highest redshift panels are based on ESI data and the two lowest on HIRES data. In each case we have overplotted the distribution obtained from the core high-S/N quasar sample. For the ESI data we have smoothed the comparison sample to the ESI resolution. Rather than show Poisson error bars, which underestimate the errors because of correlation effects, we have shown in each case the range of the five quasars. There is very little change in the shape of the distribution over the redshift interval, which is consistent with the results of the Voigt profile analyses.

The slow change in the overall ion densities and the invariance of the distribution functions appear to suggest that contemporary injection must not be a dominant mechanism for producing the observed absorption lines, since we would in that case expect the features to track the evolution of the star-forming galaxies and to have some dependence on the changing properties of these objects. Indeed, even if this were the only mechanism present, we would expect that metals ejected by previous generations of star-forming galaxies would build up in the intergalactic gas, and that as time progressed the relative numbers of these versus those being formed by contemporary injection would change, so producing evolution in the column density distribution with redshift. However, such effects could be concealed if the ejected material becomes too hot to be observed as C iv (Aguirre et al. 2005), and in Paper II we will look at other approaches to determining the fraction of the lines that arise in contemporary injection.

6. CONCLUSION

We have described a novel objective pixel optical depth technique, superPOD, that uses the doublet nature of the common ions C iv and Si iv, which are the principal metal tracers in the intergalactic medium outside of the Lyα forest, to analyze the properties of metals in the high-redshift intergalactic medium using a sample of extremely high S/N Keck HIRES and ESI spectra of 26 quasars between redshifts 2.1 and 6.4. The method is completely objective and, using statistical corrections for contamination by other lines, telluric absorption, bad pixels, continuum fitting, etc. and for incompleteness, gives us an increased sensitivity of approximately 0.5 dex over previous analyses.

As a check on the method, we have reproduced the conventional analysis using a percolation method to generate pseudoclouds from ion optical depths. Using this set of pseudoclouds we confirm that the C iv column density distribution remains essentially invariant, with slope $-1.44$, from $z = 1.5$ to 5, which confirms the lack of redshift evolution of $\Omega(C iv)$ for $z = 2–5$ previously determined from conventional Voigt profile fitting analysis.

The pseudoclouds also give information on the column density environment of a given optical depth; for the higher resolution HIRES data there is a tight relation, $\tau \sim N^{-0.7}$, between the peak optical depth and the column density. Using the optical depths directly, we show that there is little evolution in C iv and C iv/C iv from $z = 2$ to 5, although there is a downturn of at least a factor of 2 in $\Omega(C iv)$ and $\Omega(Si iv)$ above $z = 5$; we do, however, see substantial evolution in Si iv/C iv.

We will use this technique in two subsequent papers to investigate what fraction of the absorbers lie in galactic wind outflows (Paper II) and what metallicity is associated with regions of $\tau(Ly\alpha) < 1$ (Paper III).

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REFERENCES

Adelberger, K. L., Steidel, C. C., Shapley, A., & Pettini, M. 2003, ApJ, 584, 45

Aguirre, A., Schaye, J., Hernquist, L., Kay, S., Springel, V., & Theuns, T. 2005, ApJ, 620, L13

Aguirre, A., Schaye, J., Kim, T.-S., Theuns, T., Rauch, M., & Sargent, W. L. W. 2004, ApJ, 602, 38

Aguirre, A., Schaye, J., & Theuns, T. 2002, ApJ, 576, 1

Aracil, B., Petitjean, P., Pichon, C., & Bergeron, J. 2004, A&A, 419, 811

Bromm, V., Yoshida, N., & Hernquist, L. 2003, ApJ, 596, L135

Cowie, L. L., & Songaila, A. 1998, Nature, 394, 44

Cowie, L. L., & Songaila, A., Kim, T.-S., & Hu, E. M. 1995, AJ, 109, 1522

Daigne, F., Olive, K. A., Vangioni-Flam, E., Silk, J., & Audouze, J. 2004, ApJ, 617, 693

D’Odorico, S., Cristiani, S., Dekker, H., Hill, V., Kaufer, A., Kim, T.-S., & Primas, F. 2000, Proc. SPIE, 4005, 121

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

Fujita, A., Mac Low, M.-M., Ferrara, A., & Meiksin, A. 2004, ApJ, 613, 159

Mackey, J., Bromm, V., & Hernquist, L. 2003, ApJ, 586, 1

Madau, P., Ferrara, A., & Rees, M. J. 2001, ApJ, 555, 92

Meyer, D. M., & York, D. G. 1987, ApJ, 315, L5

Pettini, M., Madau, P., Bolte, M., Prochaska, J. X., Ellison, S. L., & Fan, X. 2003, ApJ, 594, 695

Pettini, M., Steidel, C. C., Adelberger, K. L., Dickinson, M., & Giavalisco, M. 2000, ApJ, 528, 96

Pichon, C., Scannapieco, E., Aracil, B., Petitjean, P., Aubert, D., Bergeron, J., & Colombi, S. 2003, ApJ, 597, L97
Qian, Y.-Z., Sargent, W. L. W., & Wasserburg, G. J. 2002, ApJ, 569, L61
Schaye, J., Aguirre, A., Kim, T.-S., Theuns, T., Rauch, M., & Sargent, W. L. W. 2003, ApJ, 596, 768
Sheinis, A. I., Miller, J. S., Bolte, M., & Sutin, B. M. 2000, Proc. SPIE, 4008, 522
Simcoe, R. A., Sargent, W. L. W., & Rauch, M. 2004, ApJ, 606, 92
Songaila, A. 1997, ApJ, 490, L1
———. 1998, AJ, 115, 2184

Songaila, A. 2001, ApJ, 561, L153
Songaila, A., & Cowie, L. L. 1996, AJ, 112, 335
Tytler, D., Fan, X.-M., Burles, S., Cottrell, L., Davis, C., Kirkman, D., & Zuo, L. 1995, in QSO Absorption Lines, ed. G. Meylan (Berlin: Springer), 289
Venkatesan, A., & Truran, J. 2003, ApJ, 594, L1
Vogt, S. S., et al. 1994, Proc. SPIE, 2198, 362
Wasserburg, G. J., & Qian, Y.-Z. 2000, ApJ, 538, L99
Yoshida, N., Bromm, V., & Hernquist, L. 2004, ApJ, 605, 579