The methods by which one characterizes the distribution of matter in cosmological simulations is intrinsically different from how one performs the same task observationally. In this paper, we make substantial steps toward comparing simulations and observations of the intergalactic medium (IGM) in a more sensible way. We present a pipeline that generates and fits synthetic QSO absorption spectra using sight lines cast through a cosmological simulation, and simultaneously identifies structure by directly analyzing the variations in H\textsc{i} and O\textsc{vi} number density. We compare synthetic absorption spectra with a less observationally motivated, but more straightforward density threshold-based method for finding absorbers. Our efforts focus on H\textsc{i} and O\textsc{vi} to better characterize the warm/hot IGM, a subset of the IGM that is challenging to conclusively identify observationally. We find that the two methods trace roughly the same quantities of H\textsc{i} and O\textsc{vi} above observable column density limits, but the synthetic spectra typically identify more substructure in absorbers. We use both methods to characterize H\textsc{i} and O\textsc{vi} absorber properties. We find that both integrated and differential column density distributions from both methods generally agree with observations. The distribution of Doppler parameters between the two methods are similar for Ly\textsc{a} and compare reasonably with observational results, but while the two methods agree with each other with O\textsc{vi} systems, they both are systematically different from observations. We find a strong correlation between O\textsc{vi} baryon fraction and O\textsc{vi} column density. We also discuss a possible bimodality in the temperature distribution of the gas traced by O\textsc{vi}.

Key words: cosmology: observations – intergalactic medium – methods: numerical – quasars: absorption lines – ultraviolet: general

Online-only material: color figures

1. INTRODUCTION

It is now well accepted that a large portion of all baryons at $z = 0$, up to $\sim$60%, exist in a phase that is extremely difficult to detect. Unlike at high redshift ($z \gtrsim 4$) where nearly all baryons are accountable through Ly\textsc{a} absorption (Rauch et al. 1997; Prochaska & Tumlinson 2009), only $\sim$30% are observed to be associated with the cool, photoionized Ly\textsc{a} forest today (Persic & Salucci 1992; Bristow & Phillipps 1994; Fukugita et al. 1998; Fukugita & Peebles 2004; Danforth & Shull 2008; Shull et al. 2012), with only an additional $\sim$10% in galaxies. However, it has been shown by cosmological simulations (e.g., Cen & Ostriker 1999; Davé et al. 1999, 2001; Smith et al. 2011) that most of these “missing baryons” still exist in the intergalactic medium (IGM), but have simply been heated through a combination of accretion shocks from structure formation and feedback from galaxies to temperatures too hot ($\sim 10^6$–$10^7$ K) to be easily traceable with neutral hydrogen. Because of these extreme temperatures, this so-called warm/hot intergalactic medium (WHIM) can only be traced through absorption lines of highly ionized metals, such as O\textsc{vi} and Ne\textsc{vii} at ultraviolet wavelengths, and O\textsc{vii} and O\textsc{viii} in the X-ray. To date, the O\textsc{vi} doublet at $\lambda \lambda 1032, 1038$ has proven to be the most fruitful of these detection methods, with numerous large samples having been compiled (Danforth & Shull 2005, 2008; Danforth et al. 2006, 2014; Tripp et al. 2008; Thom & Chen 2008a, 2008b; Tilton et al. 2012; Savage et al. 2014), providing an excellent benchmark for simulations.

Numerous simulation studies have succeeded at reproducing the observed number density per unit redshift $dN/dz$ of O\textsc{vi} absorbers (Cen & Fang 2006; Oppenheimer & Davé 2009; Smith et al. 2011; Cen & Chisari 2011; Tepper-García et al. 2011; Oppenheimer et al. 2012; Cen 2012), despite making significantly different predictions as to the physical conditions of the associated gas. For example, Oppenheimer & Davé (2009) and Oppenheimer et al. (2012) find that an overwhelming majority of O\textsc{vi} absorbers are associated with cool, photoionized gas with a mean temperature of $\sim 15,000$ K. On the other hand, Smith et al. (2011) and Shull et al. (2012) find that O\textsc{vi} absorbers come from gas in two distinct temperature regimes—a photoionized component at $T \sim 30,000$ K and a hotter, collisionally ionized component at $T \sim 300,000$ K, comprising $\sim$35% and $\sim$55% of all O\textsc{vi} absorption, respectively (with the remaining 10% contained in collapsed structures). Tepper-García et al. (2011) find a similar distribution of O\textsc{vi} as Smith et al. (2011) in their simulated volume, but O\textsc{vi} absorption is biased toward detecting the hotter, collisionally ionized phase. Some of these disagreements may arise from differences in the simulations, such as the methods by which metals are injected and mixed into the IGM by the feedback scheme, but another potential source of difference is the method in which synthetic O\textsc{vi} absorbers are created and analyzed in these works. Oppenheimer & Davé (2009), Tepper-García et al. (2011), and Oppenheimer et al. (2012) create synthetic absorption spectra which are then analyzed in a fashion similar to actual observations. However, Smith et al. (2011) create...
absorbers simply by summing the total column density along a small section of a randomly oriented line of sight in their simulation box.

In this paper we present a re-analysis of a simulation from Smith et al. (2011), with the intent being to better understand the correspondence between absorption lines and the physical conditions with which they are associated, and to better understand possible systematics between the usage of different means of extracting absorber data from simulations. To accomplish this, we create a sophisticated pipeline for fitting absorption-line spectra that can be used for both synthetic and actual absorption spectra. Our primary goal is to understand the systematic differences between quantities inferred from absorption lines in synthetic spectra and quantities derived more directly from the simulation outputs. In Section 2, we describe briefly the simulation upon which our analysis is focused. In Section 3, we detail three different methods of varying sophistication that we use to create synthetic absorber samples. In Section 4, we examine a range of properties of the synthetic Lyα and O vi absorbers created using each of these three methods, comparing each method both to the other two and to observations of the statistical properties of real quasar absorption line systems. We provide a discussion of our results in Section 5, and summarize in Section 6.

2. SIMULATION

In this work, we analyze a simulation performed with the open source cosmological adaptive mesh refinement + N-body code, Enzo (The Enzo Collaboration et al. 2013; O’Shea et al. 2004; Norman et al. 2007). The simulation, which is run 50_1024_2 from Smith et al. (2011), has a comoving box size of 50 Mpc $h^{-1}$ with 1024$^3$ grid cells and dark matter particles, corresponding to a comoving spatial resolution of 49 kpc $h^{-1}$ and a dark matter particle mass of $7 \times 10^6 M_{\odot}$. The simulation includes the metallicity dependent radiative cooling method of Smith et al. (2008), modified to include a metagalactic UV background and a modified version of the star formation and feedback method of Cen & Ostriker (1992) that injects stellar feedback into a $3 \times 3 \times 3$ cube of grid cells centered on the star particle (referred to in Smith et al. (2011) as the “distributed” method). Note that the distributed feedback method does not take into account a physical scale, it suffers from the same overproduction of stars and metals as its predecessor when used with higher resolution simulations. However, Smith et al. (2011) have shown that this simulation is able to reasonably reproduce both the observed global star formation history (Hopkins & Beacom 2006) and the number density of O vi absorbers per unit redshift ($dN/dz$) in the redshift range $0 \leq z \leq 0.4$. Smith et al. (2011) performed simulations using two different stellar feedback models. However, since the goal of this work is to understand how the statistics of synthetic absorbers are affected by the method with which they are produced, we choose to focus on just the single simulation from Smith et al. (2011) that best matched observations.

3. APPROACHES TO IDENTIFYING IGM ABSORBERS

Using the simulations described in Section 2 and the yt analysis toolkit (Turk et al. 2011), we generate 2000 pencil-beam data arrays meant to be representative of QSO sight lines. Each line of sight extends from $z = 0$ to $z = 0.4$ and has a random starting position in $(x, y, z)$ and random orientation in $(\theta, \phi)$. As the physical distance corresponding to $\Delta z = 0.4$ is much larger than the extent of the simulation box size at low redshifts, the line of sight generation tool stacks rays from multiple epochs together. This is accomplished by pre-calculating the number of data outputs and the corresponding position in redshift space needed to traverse the full length of the desired sample. All pertinent information is recorded for each cell intersected by a line of sight, including baryon density, metallicity, ion densities, ion fractions, and temperature. The pathlength $dl$ of the ray as it passes through the cell is also recorded; this length is not constant given the random orientation of the sight line, but is on the order of the resolution of the simulation.

The methods with which observers find structure in the universe is intrinsically different than the ways simulators approach the same problem. Even after generating lines of sight, simulators still have access to all the information retained by the pixels along the line of sight, or “ixels” as per Smith et al. (2011), from temperature to specific number densities. Observationally, we are limited to interpreting these quantities through indirect methods such as fitting absorption lines, apparent optical depth, or pixel optical depth. Each of these approaches is susceptible to its own systematic effects that may make it difficult to compare them. By performing both an observationally motivated analysis technique as well as a computational one on the same lines of sight we can better correlate the products of simulations with actual observations. Thus, in the following sections we will detail several methods with which we analyzed our synthetic lines of sight; one, the “spectral” method, that uses only absorption line fits of synthetic spectra and two approaches, the “contour” and “cut” methods, that utilize cell-by-cell output. A sample of the results of identification of absorbers using these methods can be seen in Figure 1. The relevant number densities ($N_{H_I}, N_{O_{VI}}$) are computed in both photo- and collisional ionization equilibrium, with the former assuming a uniform Haardt & Madau (2001) radiation background.

For each method, after generating a full set of absorbers we filter by column density and only include H I absorbers with column densities $N$ (cm$^{-2}$) in the range $12.5 \leq \log N_{H_I} \leq 17.2$ and O vi absorbers with column densities in the range $12.5 \leq \log N_{O_{VI}} \leq 15.2$. We restrict our column density range on the higher end to reflect the absence of radiative transfer in our simulation. On the low end we restrict our column density range to reflect observable limits.

3.1. Spectral Method

In order to mimic true observations with the data generated via simulation, a synthetic QSO absorption spectrum was created and then fitted for each line of sight. The fitted components then determined the absorber—in particular, the absorber’s column density and Doppler-value. This method will henceforth be referred to as the “spectral method.”

3.1.1. Creating Absorption Spectra

For each of the 2000 simulated QSO sight lines we create a corresponding absorption spectrum by considering the effects of absorption for each pixel of gas. The optical depth for a cloud of gas with column density $N$ of a wavelength $\lambda$ is given by $\tau(\lambda) = C_i N a H(a, x(\lambda))$, where $x = (\lambda - \lambda_a)/\lambda_a$, $a = \Gamma_i/(4\pi \Delta \nu D)$, and $C_i$ is a transition-dependent constant. Here $\Delta \nu D = b_\nu/(c \lambda_i)$ and $\Gamma_i$ is the reciprocal of the mean.
As each lixel generates its own Voigt profile, large scale features in the spectra are typically composed of contributions from multiple lixels and their corresponding column densities. This effect can be seen in Figure 1 where, despite a wide range of HI number densities over a number of cells, only four significant spectral features are visible. This causes a degeneracy in our notion of $b$-value, since broadening can occur as a result of disordered line-of-sight motion within a cloud of gas (as a result of, e.g., turbulence) in addition to the broadening due to thermal motion. Cells with different velocities create Voigt profiles at slightly different wavelengths due to the Doppler effect and, as a result, the overall line to looks broader. This broadening is typically indistinguishable from the broadening due to thermal motion.

In generation of the spectrum as many ions as desired can be included. Fitting a single ion at a time removes any ambiguity of what ion is being analyzed, so all further analysis was completed in this manner. Our spectra were also fit without the effects of noise as an initial test of our methods, though we note that the method works with noisy spectra as well.

3.1.2. Fitting Absorption Spectra

Due to the challenge of fitting a large number of synthetic spectra, we developed an automated line-fitting pipeline. This system takes the synthetic spectra and fits a series of Voigt profiles to each spectrum in a completely automated fashion. To automatically identify absorbers, each contiguous region with normalized flux below an adjustable cut-off ($F/F_{\text{cont}} = 0.99$) is identified. This cut-off was chosen primarily to underestimate the observable limit due to noise limitations, without over-fitting very shallow and hard-to-detect lines. Lowering this value by a few percent does not significantly affect results. Raising the value begins to substantially increase computational cost as regions become larger and a typical region contains more lines; however, the results are not typically affected as a region is generally considered successfully fit regardless of the inclusion of the smaller fluctuations.

Exceptionally large complexes ($\Delta \lambda > 50 \text{Å}$) with multiple lines are broken up at points of minimum absorption, if that minimum point has a flux within a few percent of the adjustable cutoff. This is done to prevent very large regions from dramatically slowing down the fitting procedure due to the difficulty of optimizing the fits of many lines simultaneously.

Each region is then taken in turn from minimum to maximum wavelength and fit by iteratively adding and adjusting Voigt profile parameters (column density, broadening value, and redshift) using the least squares method until the total $\chi^2$ error is smaller than an acceptable fractional error threshold ($10^{-4}$) multiplied by the number of points in the region in units of normalized flux. We attempt to fit up to eight individual components simultaneously. If this is unsuccessful or if the error begins to increase upon adding more components, the fit is accepted if the total error is within two orders of magnitude of the desired error. Given the stringent conditions used for our standard fitting procedure, these fits are typically quite good, and would certainly be acceptable if noise were included in our synthetic spectra (which we defer to a later paper). Changing the value of the acceptable fractional error threshold by an order of magnitude has little effect on the overall results.

In cases of ions that create more than one line (as in the O\textsc{vi} doublet), the lower wavelength line is fit to the region as, in the case of Li-like ions (2s$\rightarrow$2p), this is the stronger line. We then attempt to fit the higher wavelength...
line with the parameters calculated for the lower wavelength counterpart and if the resulting total fit has a low enough error then it is accepted. This allows some amount of leeway for blanketed line identification where a large line occurs in the same wavelength space as another smaller line, effectively hiding the smaller line.

An example of this fitting procedure is shown in Figure 2. Once the region is identified, a single line is optimized to fit the whole region. Given the structure of the region, a single line is insufficient to constrain the region and the difference between the fit and the data is still larger than allowed by the average error per point. Thus, another line is added and the region is fit and the data is still larger than allowed by the average error per point bound and the region is rejected. This process is illustrated in Figure 3. Multiple lines for a total of nine free parameters. The three-line fit approach is used. Absorbers with low temperatures \(T \ll 10^4\) \(K\) and relatively high column densities \(N_{\text{HI}} \sim 10^{18} \text{ cm}^{-2}\) generate Voigt profiles with damping wings. Typical parameters that are appropriate for the large majority of absorbers often fail to converge to a good fit for absorbers with these properties. When such a region is identified, a separate set of widely varied initial temperatures and column densities are tried, which allows for a more accurate fit at the expense of substantially increased computational cost. In this paper we primarily examine \(\text{H} \text{I}\) and \(\text{O} \text{VI}\) absorption. Most of the challenging fits are of \(\text{H} \text{I}\) absorbers, due to their more varied (and higher) column densities and environments.

![Figure 2. Example Ly\alpha fit for a region of wavelength space where the best fit consists of multiple line components. The x-axis indicates wavelength difference measured from an arbitrary reference wavelength, and the y-axis indicates normalized flux. The solid blue line indicates the total normalized flux generated from a range of \(\text{H} \text{I}\) number density along a line of sight, while the dashed lines indicate components found for the fit. (A color version of this figure is available in the online journal.)](image-url)

### 3.2. Cut Method

Instead of creating absorption spectra, simulators have the opportunity to examine exactly how number density and other physical quantities vary with redshift along a line of sight. However, in order to compare with observation, it is necessary to break up this continuous variation into discrete absorbing structures. A simple approach, henceforth referred to as the “cut method,” was employed by Smith et al. (2011) in a previous analysis of the simulations examined in this paper. In this method, a given line of sight is cut into pieces of constant length in redshift space where the cells between each cut contribute to that absorber. The sampling resolution \(\Delta \lambda / \lambda\) is set at 5000; this allows smoothing of the region over multiple pixels while maintaining a constant resolution in the range of observation. A change of resolution by an order of magnitude in either direction does not significantly affect the results.

The column density for ion \(x\) is given by the sum over cells \(N_x = \sum d_l n_{x,i}\), where \(d_l\) is the pathlength and \(n_{x,i}\) is the number density of ion \(x\) in a given absorber species in a given cell. The \(b\)-value is comprised of a thermal and a non-thermal component for a total \(b\)-value given by \(b = \sqrt{b^2_\text{th} + (\sigma)^2}\). The thermal component is the same as the spectral thermal Doppler parameter, \(b_\text{th} = \sqrt{2kT/m_i}\). To approximate the non-thermal component of broadening we find the variance in the line of sight velocities weighted by column density of each cell. All other relevant quantities such as ion fraction, metallicity, and temperature are found via column density-weighted average for all cells contributing to the absorber.

This method is simple because it requires no additional analysis beyond dividing the line of sight properties into equal redshift bins; however, it does not identify physical structures at all. Large absorbers may happen to fall along the boundary of two redshift bins as seen at \(z \sim 0.085\) in Figure 1. This may cause a single region to be interpreted as multiple absorbers of lower column density and distort the inferred physical conditions associated with the absorber. Although properties dominated by the sharp peaks in number density may still hold, this method cannot be expected to give good intuition for the physical nature of a structure because, quite simply, the method of defining absorbers in not based on physics, but rather numerically convenient quantities.

### 3.3. Contour Method

The “contour method” of defining IGM absorbers was developed in response to the limitations of the cut method described in Section 3.2. Instead of cutting blindly by redshift, regions are identified where groups of spatially contiguous cells all have number densities above the mean number density of a given species. A discussion of identifying the mean number density of each species is given in Section 4.1, but the values adopted for the remained of this work are \(n_{\text{HI}} = 10^{-14} \text{ cm}^{-3}\) and \(n_{\text{OVI}} = 10^{-22} \text{ cm}^{-3}\). For each region, a peak species number density is determined. An absorber is then quantified as spatially contiguous cells within the original region with number densities above a characteristic density, set by some fraction of the peak number density. For most of the following analysis we chose the characteristic density as 0.5 times the peak number density, but the effects of varying this fraction are investigated in Section 4.1. This process is illustrated in Figure 3. Multiple absorbers can be identified in a single region as illustrated in Figure 1 at \(z \sim 0.086\). By setting a characteristic density for each region rather than a single number density cutoff for the
the effects of a poor choice in characteristic density fraction could affect column density weighted properties for absorbers of a given species. The constant fit for the tail of the distribution, $b$, reflects the average ion number density of the regions between absorbers. This number density is adopted as the mean number density of the species, but again this mean refers to the mean of the background between absorbers, not the mean number density of the entire volume or a given sightline. We note that the constant background value is a very low O vi number density. Examination of the raw simulation data shows that these values correspond to cells in the simulation volume with baryon densities of $10^{-3}$–$10^{-1}$ of the cosmic mean, metallicities of $10^{-4}$–$10^{-2} Z_\odot$, and temperatures of $10^5$ K or below (resulting in O vi fractions of $10^{-7}$ or below at the densities in question when the metagalactic ultraviolet background is taken into consideration).

We recognize that due to the shallowness of the power law for H i number density ($\alpha_{\text{H}i} = -2.4$), varying the characteristic density fraction may affect the properties of the absorbers, especially if a very low characteristic density fraction is chosen. In this case, contour-identified absorbers will fail to reflect actual structures, and quantities that should be dominated by peak values will begin to deviate due to the large excess of sampled material. O vi should be much less sensitive to the choice in cutoff given the steepness of the power law ($\alpha_{\text{O}vi} = -6.3$).

This intuition is reflected in Figure 5, where we show number of absorbers, line of sight size, and $b$ as a function of column density for a variety of characteristic density fractions. For each cutoff, a corresponding set of absorbers is found independently. This analysis is performed for a subset of the total light rays; however, the results are representative of the total sample. We find as expected that most quantities are fairly robust to changing characteristic density fraction, as displayed by the consistency of the $b$-value results. The linear size of absorbers, which is not weighted by number density, increases dramatically when lowering the characteristic density fraction. We further investigate the size as a function of column density in Section 4.1.1. Given the later results we chose a characteristic density that is 0.5 times the absorber’s maximum baryon density.

4. RESULTS

4.1. Choosing an Appropriate Contour Cut-off Density

As discussed in Section 3.3, for each spatially contiguous region of cells above the mean number density the characteristic density is calculated as some fraction of the peak number density of the region. Absorbers are then determined by spatially contiguous cells above the characteristic density. Thus, lowering or raising the characteristic density fraction could affect the number of absorbers and the extent of individual absorbers. As the effects of a poor choice in characteristic density fraction are not immediately obvious, appropriate care must be taken to select a reasonable value.

To check that the characteristic density approach is reasonable at all we examine Figure 4, where we average the number densities for a set of absorbers with low column densities ($N_{\text{H}i} = 10^{12}$–$10^{13}$ cm$^{-2}$, $N_{\text{O}vi} = 10^{13}$–$10^{13.5}$ cm$^{-2}$) over physical distance along the line of sight from the peak number density for the region. A total of 5692 and 1319 absorbers were used for Ly$\alpha$ and O vi respectively. The solid line indicates the average number density, and the shaded region shows 1$\sigma$ deviations. The averages were taken by creating bins of physical distance and, for every absorber, assigning the pixel with the most closely corresponding physical distance from peak number density to the appropriate bin. We then fit the resulting distribution with a power law at small radii and a constant at larger radii (i.e., we fit $n(r) = r^\alpha + b$ for $r < d$ and $n(r) = n_o$ for $r > d$). The slope of the power law, $\alpha$, allows us to assess the extent to which an absorber will be dominated by its peak, and correspondingly, how much a change in characteristic density fraction could affect column density weighted properties for absorbers of a given species. The constant fit for the tail of the distribution, $b$, reflects the average ion number density of the regions between absorbers. This number density is adopted as the mean number density of the species, but again this mean refers to the mean of the background between absorbers, not the mean number density of the entire volume or a given sightline. We note that the constant background value is a very low O vi number density. Examination of the raw simulation data shows that these values correspond to cells in the simulation volume with baryon densities of $10^{-3}$–$10^{-1}$ of the cosmic mean, metallicities of $10^{-4}$–$10^{-2} Z_\odot$, and temperatures of $10^5$ K or below (resulting in O vi fractions of $10^{-7}$ or below at the densities in question when the metagalactic ultraviolet background is taken into consideration).

We recognize that due to the shallowness of the power law for H i number density ($\alpha_{\text{H}i} = -2.4$), varying the characteristic density fraction may affect the properties of the absorbers, especially if a very low characteristic density fraction is chosen. In this case, contour-identified absorbers will fail to reflect actual structures, and quantities that should be dominated by peak values will begin to deviate due to the large excess of sampled material. O vi should be much less sensitive to the choice in cutoff given the steepness of the power law ($\alpha_{\text{O}vi} = -6.3$).

This intuition is reflected in Figure 5, where we show number of absorbers, line of sight size, and $b$ as a function of column density for a variety of characteristic density fractions. For each cutoff, a corresponding set of absorbers is found independently. This analysis is performed for a subset of the total light rays; however, the results are representative of the total sample. We find as expected that most quantities are fairly robust to changing characteristic density fraction, as displayed by the consistency of the $b$-value results. The linear size of absorbers, which is not weighted by number density, increases dramatically when lowering the characteristic density fraction. We further investigate the size as a function of column density in Section 4.1.1. Given the later results we chose a characteristic density that is 0.5 times the absorber’s maximum baryon density.

4.1.1. Absorber Size

As absorber size was the most clearly varying parameter with characteristic density fraction, it is a useful metric to assess the choice of said fraction. Analytic estimates (Schaye 2001) give an expected size–column density relation of $L \propto N^{-1/2}$ for H i absorbers. In Figure 6 we plot mean absorber size as a function of column density for H i and O vi. We also overplot a line of best fit for the size–column relation obtained through a least squares fit of the median value in each column density bin weighted by the number of absorbers in the bin. We find a best-fit power law of $-0.12$ for H i, which is substantially shallower than the expected slope of $-1/3$. For O vi we find a power law of $-0.12$.

4.2. Comparison of Methods

4.2.1. Comparison of Contour and Cut Methods

Although we do not expect a priori that the cut and contour methods will give identical results, we give a short comparison of these methods. It is important to show comparison to the cut method despite its lack of physical motivation, as it was used for a previous analysis of these simulations in Smith et al. (2011). In order to correlate the absorbers, each absorber from the contour method is matched by redshift with an absorber from the cut method.
Figure 4. Average number density as a function of distance along the line of sight from the center of an absorber. The shaded region shows $1\sigma$ deviations. All absorbers with column density in range $(10^{12}–10^{13} \text{ cm}^{-2})$ for $\text{H}i$ (left) and $(10^{12}–10^{14} \text{ cm}^{-2})$ for $\text{O}vi$ (right) identified with the contour method. The center of the absorber is defined as the lixel with the highest number density. The dashed line indicates a power-law fit of the average number density. We adopt cutoff densities of $10^{-12} \text{ cm}^{-3}$ ($\text{H}i$) and $10^{-13} \text{ cm}^{-3}$ ($\text{O}vi$).

Figure 5. Absorbers were identified using the contour method for a variety of characteristic density fractions (colors). For each set of identified absorbers number of absorbers (top), average $b$-value (middle), and average size (bottom) were found as a function of column density. Left: $\text{H}i$ absorbers, Right: $\text{O}vi$ absorbers.

Matching absorbers between methods is accomplished by finding an absorber from the contour method within a given redshift ($\delta z = 10^{-6}$) of an absorber from the cut method. This process is then repeated several times after increasing the tolerance by an order of magnitude until $\delta z = 10^{-3}$. As the redshift range we consider ($0 \leq z \leq 0.4$) is quite small in comparison to the range of redshift windows we consider, we do not bother to use a window of size $\delta z/(1 + z)$. We have chosen to match the absorbers in this way to create a robust way of matching as many absorbers as possible, while still ensuring that the matches are as accurate as possible. Changing the start and end tolerances by an order of magnitude has minimal effect on the final matches, as long as the matching is accomplished using a series of monotonically increasing window sizes.

The column densities of each method for the appropriately matched and then binned by contour column density. Median contour and cut column densities and first and fourth quartiles were found for each bin. This comparison, shown in the lower panels of Figure 7, indicates no obvious systematic difference at any column density. This is indicative of the absorbers being dominated by the sharp peaks in number density. Additionally, the total number of Ly$\alpha$ absorbers found at low column densities, shown in the upper panel of Figure 7, is slightly larger when using the cut method. This is evidence of the splitting effect, as more absorbers of low column will be found when a single physical feature is inappropriately identified as two absorbers.

Given that these results show a comparable column density result, the contour method is clearly an adequate substitute in analyzing the direct output. Furthermore, since the contour method finds fewer total absorbers than the cut method (as it effectively combines multiple artificially segmented absorbers into a single, physically meaningful object), as well as absorbers that directly correlate to the actual cosmological structure in the simulation volume, it is straightforward to correlate absorbers found with the contour method with those found using the spectral method. Thus, all of the analysis in the following sections of this paper will be completed using values found through the contour method.

4.2.2. Comparison of Contour and Spectral Methods

We perform an analysis similar to Section 4.2.1 in comparing the contour and spectral methods, and show this comparison in Figure 8. After matching absorbers from the contour method with the column density determined by a single component line fit using the spectral method technique, the contour absorbers were then binned by column density. The median spectral and contour column densities for the absorbers in each of these bins was then plotted with error bars showing the corresponding first and fourth quartiles for each bin. These matches were
determined using the same increasing redshift tolerance process as described in Section 4.2.1.

We find that for Lyα the pipeline has significant trouble appropriately matching corresponding absorbers at all column densities and significantly underpredicts the results from the contour method. For O VI the contour method finds higher column densities by approximately a factor of two for low column densities ($N_{OVI} = 10^{12}$–$10^{14}$ cm$^{-2}$) and increasing to an order of magnitude for higher column densities ($N_{OVI} = 10^{14}$–$10^{16}$ cm$^{-2}$).

This is expected as the spectral method is not biased against using multiple component fits if the $\chi^2$ error is lower in using more components. In order to negate this effect, we sum together components identified in the same complex. A complex is defined as a contiguous region with a flux less than $F/F_{continuum} = 0.99$. The total column density of the region is thus $N_{total} = \sum N_i$. The redshift of the complex is slightly more difficult to define, but we use a column density weighted average to assign a single value of redshift to the entire complex. Performing the analysis in this way loses some information about physical structure from line of sight velocities that the spectral method is able to identify, but allows us to check if the two methods track similar amounts of total material.

As seen in Figure 9, matching the contour method absorbers to a line complex rather than a line component gives more comparable column density results for Lyα and O VI at all column densities. There is a larger scatter about the mean for absorbers with higher column densities ($N_{HI} \geq 10^{16}$ cm$^{-2}$).
Contour log \(N_{\text{HI}}\) [cm\(^{-2}\)]

Figure 9. Contour absorbers were binned by column density and the median column density of the matching spectral absorbers was plotted against the median column density of the contour absorbers for that bin with vertical error bars showing first and fourth quartiles in spectral column density. Dashed line shows \(N_{\text{contour}} = N_{\text{spectral}}\). The spectral method combines each component found in multi-component fits of a line complex into a single absorber whose column density is the sum of the components’ column densities. Left: H\(_1\) absorbers. Right: O\(_{VI}\) absorbers.

\(N_{\text{OVI}} \geq 10^{14.5} \text{ cm}^{-2}\). This may be indicative of the difficulty of fitting saturated lines. We can now be reasonably certain that the spectral and contour methods identify the same absorbing structures, and we can match them reasonably effectively. The spectral method may find different underlying IGM substructure than the contour method due to line of sight velocity effects, but the two methods find roughly equivalent bulk material.

In Figure 10 we compare the distribution of \(b\)-values for H\(_1\) and O\(_{VI}\) absorbers over slices in column density. The slices were chosen to give a relative idea of how the methods compare for absorbers of interest; as such, we do not show higher column density slices for H\(_1\), despite the fact that higher column absorbers are fit. We find that for H\(_1\), the distribution of \(b\)-values is shifted for the spectral method relative to the contour method at low column \((10^{13} \leq N \leq 10^{13.5} \text{ cm}^{-2})\) with the peak of the spectral distribution at 25 km s\(^{-1}\) compared to 20 km s\(^{-1}\) for the contour method. For increasing column density slices this distinction shifts with spectral the spectral distribution peaking around 30 km s\(^{-1}\) and the contour distribution peaking around 25 km s\(^{-1}\). The O\(_{VI}\) distributions look quite distinct for all column density slices. It seems that compared to the contour method, the spectral method identifies an overabundance of low column absorbers with very low \(b\)-values as well as a relative lack of high column absorbers with higher \(b\)-values.

4.3. Comparison to Observations

We now compare our synthetic absorber population with observed absorbers to assess any systematic differences, attributable to our simulation or methods.

Figure 10. Histogram of \(b\)-values for absorbers with column densities in ranges \(10^{13} < N < 10^{13.5} \text{ cm}^{-2}\) (top row), \(10^{13.5} < N < 10^{14} \text{ cm}^{-2}\) (2nd row), \(10^{14} < N < 10^{14.5} \text{ cm}^{-2}\) (3rd row), and \(10^{14.5} < N < 10^{15} \text{ cm}^{-2}\) (bottom row). Red bars indicate spectral absorbers, blue bars indicate contour absorbers, and purple indicates an overlap in the distributions. Left: H\(_1\) absorbers. Right: O\(_{VI}\) absorbers.

(A color version of this figure is available in the online journal.)
A common test of the accuracy of simulations is to recreate the observed number density of O\textsc{vi} absorbers per unit redshift (Tilton et al. 2012; Danforth & Shull 2008), as well as the cumulative number density of O\textsc{vi} absorbers per unit redshift (e.g., Fang & Bryan 2001; Cen & Fang 2006; Oppenheimer et al. 2009; Tepper-García et al. 2011; Smith et al. 2011). It is thus quite useful to understand how generating this statistic from simulations using an observationally motivated method intrinsically differs from generating this statistic from absorbers found using analysis of cell-by-cell output.

Figure 11 shows this analysis for H\textsc{i} and O\textsc{vi} absorbers found in our simulation, along with observational data from Tilton et al. (2012) and Danforth & Shull (2008) for comparison for H\textsc{i} and O\textsc{vi} respectively. We consider each component of a multi-component fit of a complex separately because, although single-component fits were favored in both observational cases, complexes with clear evidence of substructure were fit in a multi-component fashion with each component listed separately in the calculation of d\textit{N}/dz. In the top row of this figure we show the cumulative line number density of H\textsc{i} and O\textsc{vi} shown in the standard way—i.e., we show the number of absorbers above a given species column density at the mean redshift of the simulation outputs, normalized by the total redshift interval \(\Delta z\) of the synthetic observations. The bottom row displays the differential line number density normalized by the total redshift interval \(\Delta z\), also known as the column density distribution function.

The two methods agree quite well at all column densities for both Ly\(\alpha\) and O\textsc{vi} as seen in both the differential and integral forms. There is a systematic under-prediction relative to the observed absorber frequency using either simulated method in O\textsc{vi}; however, this was also found in the initial analysis presented by Smith et al. (2011), and is likely to be an intrinsic property of the simulation rather than a feature of our method of determining absorber properties.
It should be noted that we consider absorbers above a column density of $10^{12.5} \text{ cm}^{-2}$ for the contour method, and fit below the observable limit for both H\textsc{i} and O\textsc{vi} with the spectral method using noiseless spectra. As a result, no significant completion correction is required for low column absorbers in our simulated results, which may result in systematic differences from the cited observational results.

### 4.3.2. Broadening Value

The other parameter that is found directly using the spectral method is the Doppler parameter, or “$b$-value.” This parameter determines the width of a line and typically has contributions from both thermal and non-thermal broadening.

While observationally these components are very challenging to distinguish and require simultaneous fits of multiple species with different masses, in a simulation we have perfect knowledge of the thermal and kinematic behavior of the plasma everywhere in our volume. To that end, a more detailed and precise study is possible. Figure 12 shows the median $b$-value plotted against column density for both the contour and spectral methods, as well as the squared fraction of total $b$-value due to thermal motion as a function of column density for the contour method. We look at the squared fraction as the thermal and non-thermal components of the total $b$-value are added in quadrature.

The Ly\textalpha values agree reasonably well between methods at lower column densities and but diverge slightly at high column densities ($N_{\text{H}i} \geq 10^{16} \text{ cm}^{-2}$). The values increase slightly with column to $N_{\text{H}i} \sim 10^{14.5} \text{ cm}^{-2}$. The $b$-values from the contour method then begin to slightly decrease again while the values derived from the spectral method remain fairly constant.

Observational results from Tripp et al. (2008) show a similar pattern as the contour method.

For O\textsc{vi}, the median $b$-value increases stays roughly constant at $b \sim 20 \text{ km s}^{-1}$ using the contour method. The spectral method stays roughly constant at $b \sim 15 \text{ km s}^{-1}$. We do not see the trend indicated by Tripp et al. (2008) of increasing $b$-value with column density for either method. We note that the biggest divergence between the two methods occurs where the thermal component of the $b$-value becomes less dominant; however, this does not cause a systematic under- or overprediction of $b$-value by either method across both species.

We note that here we only consider the $b$-values of each individual spectral component in this analysis. Although combining complexes was useful in an attempt to correlate spectral structures with contour structures as in Sections 4.2.2, this method obscures the underlying structure that can be determined with the aid of the $b$-values. We thus do not expect the contour and spectral $b$-value distributions to be the same, as they simply do not correspond to the same quantities; the contour method takes the variation in bulk motion of separate features and gives a higher non-thermal motion component of the $b$-value, whereas the spectral method divides up the same region of physical space into separate absorbing components.

### 4.4. Physical Conditions of Absorbers

In order to extend our understanding of the WHIM and its relationship to observations, we examine the physical environment associated with the absorbers identified with the contour method.
4.4.1. Median Quantities Of Absorber Systems

Figure 13 details the physical condition of the gas as a function of absorber column density. Gas temperature appears to increase and then decrease with increasing column density for HI absorbers, while the temperature of O vi absorbers decreases with increasing column. The temperature behavior for HI also typically has much less variance at a given column density. Metallicity, defined as the total mass in elements heavier than hydrogen relative to the total gas mass normalized by the solar metallicity, defined as the total mass in elements heavier than hydrogen normalized by the solar abundances. The median number density of HI increases steadily with increasing column density. There is slight increase with increasing H I column density, albeit with an increasing variance at low N HI, suggesting that low N HI systems may trace a large variety of environments. Clear trends in O vi fraction can be seen as a function of H I column density, with a peak at N HI ≃ 10^{14} cm^{-2} and lower fractions at larger and smaller columns. The median number density of H increases steadily for both H I and O vi absorbers, although over a wider range with smaller variance for H I. The O vi fraction also seems to increase with O vi column density, but the variance in this trend is far larger. These trends appear largely consistent with those initially provided by Smith et al. (2011).

4.4.2. Thermal State of O vi Absorbers

One of the primary purposes of these simulations was to investigate the utility of O vi as a tracer of the WHIM. The initial analysis presented by Smith et al. (2011) showed a bimodality in the temperature distribution of O vi also seen in Tepper-García et al. (2011). The bimodality was centered at T ~ 10^5 K, with 57% of O vi absorbers found around temperatures of 10^{5.5} K in the WHIM phase and 37% found at temperatures of 10^{4.5} K in the warm phase (and the remaining 6% found at higher densities in what Smith et al. (2011) defined as the “condensed” phase, with a baryon overdensity of Δ_b ≳ 1000). Such a bimodality suggests that both collisionally ionized and photo-ionized O vi are present in significant amounts in the IGM.

We then must ask if these statistics are proportionally recreated when looking at absorbers found using the methods presented in this paper. Smith et al. (2011) found there to be no bias between the true phase distribution of O vi in the simulation and that inferred from absorbers created with the cut method, whereas Tepper-García et al. (2011) found O vi absorption to be biased toward higher temperatures. Figure 14 shows the baryon overdensity and temperature for each absorber found using the spectral method. Baryon properties are determined by using the mean overdensity and temperature of the gas in the same absorber found with the contour method, as determined using column density-weighted averages of all cells in the absorber. The distribution shows no evidence of a strong temperature bimodality, but instead shows a roughly smooth distribution over the temperature range 4.5 < log(T/K) < 5.5. If a bimodality does exist it is only present in the very highest column absorbers. There are no significant discrepancies between the absorbers identified here with the contour method versus those identified initially with the cut method. We also find similar overall phase fractions, with 69% of O vi absorbers in the WHIM phase, 30% of absorbers in the warm phase, and 1% of absorbers in the condensed phase.

4.4.3. Cool versus Warm IGM

The WHIM is often defined as gas with temperatures in the range 10^5–10^7 K (Cen & Ostriker 1999; Davé et al. 2001). Using temperatures derived via the contour method, we attempt to determine the characteristics of observables for absorbers in this temperature range and assess any systematic differences between absorbers with lower temperatures. For this analysis we henceforth define a WHIM absorber as an absorber with T > 10^5 K and a warm absorber as one with T < 10^5 K. Figure 15 shows column density and O vi absorbers have roughly linear distribution by column density in...
Figure 14. Thermal-state distribution of O\textsc{vi} absorbers. Each absorber is plotted as a function of its mean baryon overdensity (defined as $\rho/\rho_0$) and temperature, with points colored according to absorber column density. The dashed line indicates where collisional ionization equals photoionization (collisional ionization dominates above the curve). Histograms along the top and right side of the scatter plot show overdensity and temperature, respectively, for all O\textsc{vi} absorbers with column densities greater than $10^{15}$ cm$^{-2}$ (light blue), $10^{14.5}$ cm$^{-2}$ (dark blue), $10^{14}$ cm$^{-2}$ (dark green), and $10^{13}$ cm$^{-2}$ (light green). (A color version of this figure is available in the online journal.)

Figure 15. Absorbers binned by column density (top) and $b$-value (bottom). WHIM absorbers are in blue, warm absorbers are in purple. Left: H\textsc{i} absorbers. Right: O\textsc{vi} absorbers. All absorbers have been identified using the contour method. (A color version of this figure is available in the online journal.)

logspace, while the WHIM H\textsc{i} absorbers fall off sharply after $N_{\text{H\textsc{i}}}$ $\sim$ $10^{14}$ cm$^{-2}$. The warm and WHIM O\textsc{vi} absorbers show very similar distributions by column density, with the WHIM absorbers dominating slightly below $N_{\text{O\textsc{vi}}}$ $\sim$ $10^{14}$ cm$^{-2}$. The $b$-value histograms show two distinct distributions for the WHIM and warm absorbers for both H\textsc{i} and O\textsc{vi}. H\textsc{i} warm absorbers have a peak $b$-value of 15 km s$^{-1}$ whereas WHIM absorbers peak at around 45 km s$^{-1}$. In O\textsc{vi}, warm
absorbers peak at 10 km s$^{-1}$ while WHIM absorbers peak at 20 km s$^{-1}$.

After establishing the relative distributions of absorber observables in the warm and WHIM phases, we examine the relationship between the observables. In Figure 16 we show median $b$-value plotted over column density bins. We find a general decrease in the $b$-value of an absorber with column density for WHIM phase H$\text{I}$ absorbers. A absorber with column density in the last bin appears to reverse the trend, but this point is not statistically significant. For H$\text{I}$ absorbers in the warm phase, $b$-values increase with column density until roughly $N_{\text{H}I} = 10^{15}$ cm$^{-2}$ and then begin to decrease again slightly. For O vi absorbers both the warm and WHIM absorbers have slightly increasing $b$-values with column density, but the median $b$-value of WHIM absorbers is typically 5–10 km s$^{-1}$ higher than the median $b$-value of the warm absorbers for a given column density bin.

In Figure 17 we show the fraction of WHIM absorbers out of total absorbers histogrammed two-dimensionally along column density and $b$-value. We find that above $b$-values of 40 and 15 km s$^{-1}$ for H$\text{I}$ and O vi, respectively, the fraction is dominated by WHIM absorbers. These sharp cutoffs are to be expected because for a temperature of at least 10$^5$ K there is a minimum $b$-value given by Equation (3). We also see that the higher $b$-values are associated with lower column densities, although this correlation is stronger for H$\text{I}$ absorbers.

4.4.4. Collisionally Ionized versus Photoionized O vi

In Figure 14 we plotted a dotted line indicating where collisional ionization begins to dominate over photoionization for O vi, given by

$$
\log \rho/\bar{\rho}_b = 7.68 \left( \frac{1+z}{1.2} \right)^{-3} T^{-1/2} \left( 1 + \frac{T}{1.32 \times 10^7} \right)^3 e^{1.32 \times 10^6/T} \left( \frac{1+z}{1.2} \right)^{-3} T^{-1/2} \left( 1 + \frac{T}{1.32 \times 10^7} \right)^3 
$$

(4)

derived in Shull et al. (2012), where $\bar{\rho}_b$ is the universal mean baryon density such that $\rho/\bar{\rho}_b = \Delta_b$. This relation is valid in the density regime where the IGM is optically thin to the metagalactic ionizing background, which includes all of the absorbers shown in Figure 14. In this section we perform a similar analysis as was done in Section 4.4.3, but instead of making a temperature cut to distinguish between WHIM and warm absorbers, we differentiate between absorbers where collisional ionization dominates and where photoionization dominates. As this differentiation is only appropriate for O vi, we do not show results for H$\text{I}$ absorbers here.

Figure 18 shows column density, $b$-value, and temperature histogrammed for photoionization dominated and collisional ionization dominated absorbers. The distribution of column density shows no significant difference for the two absorber populations. The $b$-value distributions both appear roughly exponential but the photoionization dominated population’s distribution peaks at $b \sim 15$ km s$^{-1}$, while the collisional ionization dominated population peaks at $b \sim 20$ km s$^{-1}$. Similarly, both temperature distributions appear roughly Gaussian with photoionization dominated peaking at $T \sim 10^5$ K and collisionally ionized dominated at $T \sim 10^{5.5}$ K.

In an approach similar to the one in Figure 17, Figure 19 shows the fraction of collisional ionization-dominated absorbers out of total absorbers in a two dimensional histogram of column density and $b$-value. The results are qualitatively similar to those seen in the O vi panel of Figure 17, but with a slightly smoother transition along the $b$-value axis.

4.4.5. Relating H$\text{I}$ and O vi

One advantage of using the contour method is that all information associated with a single grid cell is also associated with a given pixel and consequently associated with a given
absorber. This allows us to identify H\textsubscript{I} absorbers and then automatically identify the associated O\textsubscript{VI} content by summing the O\textsubscript{VI} number densities along the lixels in the absorber. Thus, after identifying H\textsubscript{I} absorbers using the contour method we find the column density of O\textsubscript{VI} associated with this H\textsubscript{I} identified set of cells. We plot this associated O\textsubscript{VI} column density as a function of the original H\textsubscript{I} number density and \textit{b}-value in Figure 20.

We find that the associated O\textsubscript{VI} column shows very different behavior for WHIM absorbers (\textit{T} > 10\textsuperscript{5} K) versus warm absorbers. In nearly all cases but the highest column H\textsubscript{I} absorbers, the associated O\textsubscript{VI} column density is significantly greater for WHIM absorbers than for warm absorbers. As a function of H\textsubscript{I} column density the O\textsubscript{VI} column for WHIM absorbers increases and then decreases, with the peak at around 10\textsuperscript{14} cm\textsuperscript{-2}. The median O\textsubscript{VI} column for warm absorbers increases fairly steadily as a function of H\textsubscript{I} column density.

The median O\textsubscript{VI} column density increases steadily as a function of \textit{b}-value starting with the minimum possible \textit{b}-value for WHIM absorbers. Warm absorbers show an initially sharp increase, but after \textit{b} \sim 60 km s\textsuperscript{-1} the points become statistically insignificant.

4.4.6. Metallicity Ionization Fraction Product

The product \((Z/Z_{\odot}) \times f_{\text{OVI}}\), where \((Z/Z_{\odot})\) is the gas metallicity in solar units and \(f_{\text{OVI}}\) is the fraction of oxygen in the O\textsubscript{VI} ionization state, is of key importance for constraining the budget of baryons traced by O\textsubscript{VI}, as given by

\[
\Omega_{b}^{\text{OVI}} = \left[ \frac{\mu_{b} H_{\odot}}{\rho_{c} (O/H)_{\odot}} \right] \int_{N_{\min}}^{N_{\max}} \frac{d^{2}N}{d\delta N} \frac{N}{Z_{\odot}(N) f_{\text{OVI}}(N)} dN,
\]

where \(\mu_{b}\) is the mean baryon mass per hydrogen, \(\rho_{c}\) is the cosmic closure density, and \((O/H)_{\odot}\) is the solar oxygen abundance.
First explored the advantage of simulations in calculating contour method to find absorbers. The product of \( \frac{Z}{Z_\odot} \) distribution when using our more physically motivated simulations using the cut method continued this study to find of each individual absorber, and previous analysis of our results.

\[ \text{Figure 21. Values of the product } \frac{Z}{Z_\odot} \times f_{\text{OVI}} \text{ over column density. The vertical gray dotted lines show limits of points that were included in averages and fit, representative of range of typical O VI surveys (Danforth & Shull 2008). The horizontal blue dashed line shows the previously assumed value of 0.02 obtained by using the standard values of } \frac{Z}{Z_\odot} = 0.1 \text{ and } f_{\text{OVI}} = 0.2. \]

Previously the product \( \frac{Z}{Z_\odot} \times f_{\text{OVI}} \) has been assumed to be constant, with typical estimates of \( \frac{Z}{Z_\odot} = 0.1 \) and \( f_{\text{OVI}} = 0.2 \), giving a product of 0.02. Tepper-García et al. (2011) first exploited the advantage of simulations in calculating \( \Omega_{\text{OVI}} \) taking into account the ionization fraction and metallicity of each individual absorber, and previous analysis of our simulations using the cut method continued this study to find that this product varied in a power-law distribution proportional to \( (N_{\text{OVI}})^{-1} \) weighted average by Shull et al. (2012). The solid yellow line indicates a power law fit of the column-limited sample of points given by \( \frac{Z}{Z_\odot} \times f_{\text{OVI}} = 0.021 \times (N_{\text{OVI}}/10^{14}\text{cm}^{-2})^{0.715}. \)

(A color version of this figure is available in the online journal.)

Creating a one-to-one correspondence of absorbers between the two methods allows us to get a sense of how well the two methods agree on column density for an arbitrary absorber. However, this method of matching is imperfect and does not always match two absorbers that correspond to the same physical structure. One way we combat this problem is by considering both spectral absorber matching of individual line components as well as total absorbing complexes. We do this to account for the cases where the spectral method finds substructure that the contour method is unable to identify.

Our spectral fitting routine does a good job of finding absorbers in a manner that is consistent with the contour method for both Lyα and O VI. Some fraction of Lyα lines with column densities in the neighborhood of \( N_{\text{HI}} \sim 10^{16} \text{ cm}^{-2} \) are difficult to fit accurately due to line saturation.

Results from the \( dN/dz \) comparison for Lyα absorbers show very good agreement outside the \( N_{\text{HI}} = 10^{16} \text{ cm}^{-2} \) range between the three methods. O VI absorbers show considerable difference with observations; however, the \( dN/dz \) values produced by the contour and spectral methods are quite consistent with each other. We hypothesize that differences between simulated and observed O VI absorption line statistics are due to ionization and feedback choices made in the underlying simulation, rather than in the methods we use to create and determine the processes of synthetic absorbers.

As the contour method does not take line of sight velocities into account when identifying absorbers we do not expect the \( b \)-values found by the spectral method to intrinsically correspond to the \( b \)-values from the contour method. Despite this difference, the two methods find comparable \( b \)-value distributions to both each other and observations (Tripp et al. 2008) for Lyα, especially at lower column densities (\( N_{\text{HI}} \leq 10^{15} \text{ cm}^{-2} \)).

There is a larger discrepancy between the contour method and the spectral method in O VI which may be an indication of line of sight velocities having a larger effect or a systematic underfitting by the spectral method. The slight systematic increase in the contour method \( b \)-values at high column densities is consistent with observations (Tripp et al. 2008) and some simulations (Cen 2012), but contrast others that find a much flatter distribution (Tepper-García et al. 2011). The \( b \)-value distribution of O VI is also much more sensitive to the method of feedback used in the 5. DISCUSSION

We have presented a reanalysis of a cosmological simulation designed to study the IGM with the aims to both better understand the systematics of the methods used to identify absorbers and better understand the gas comprising the WHIM (10^5 K \( < T < 10^7 \) K) by analyzing the physical environments associated with the absorbers. We have devised three different methods for identifying QSO absorption line systems in simulation data—the cut method, the contour method, and the spectral method. The cut method slices the line of sight into regions of equal redshift. The contour method identifies continuous regions above a number density cutoff. The spectral method fits absorption spectra generated for each line of sight. Often these methods give different results, so it is important to choose the method with care.
simulation indicating, so it is not instructive to read too much into such a comparison.

One interesting result that comes from our comparison of the two methods is the linear size–column density relation for both H\textsc{i} and O\textsc{vi}. We find (as can be seen in Figure 6) that in our calculations absorber size is a weak function of column density, with $L \propto N^{-0.12}$ for both H\textsc{i} and O\textsc{vi}. This is in disagreement with analytic predictions (e.g., Schaye 2001), though does not appear to disagree with observations. We speculate that this may be due to simulation resolution or choice of cooling model, but also note that the analytic models make the assumption of hydrostatic equilibrium, which is not necessarily accurate.

5.2. Understanding the WHIM

The physical conditions of the absorbers showed roughly the same results as found by Smith et al. (2011). The same general trends held for mean H\textsc{i} number density, metallicity, and O\textsc{vi} fraction as a function of column density.

We also find a similar phase distribution of absorbers as Smith et al. (2011) with 69% in the WHIM phase, 30% in the warm phase, and 1% in the condensed phase. We do not, however, see strong evidence for a distinct bimodality in temperature of absorbers as Smith et al. (2011) found for the phase distribution of the total gas; instead we see a smoothly varying distribution across the temperature range. This does not indicate that there cannot be two distinct collisionally ionized and photoionized populations, only that they are not represented in these absorber statistics. Such a population could still exist in the very rarest, highest column absorbers. It is also possible that these populations exist as part of a multi-phase absorber that would in effect, hide such a bimodality from observations. Further analysis could be done to examine such a distribution of gas within a single absorbing feature.

In an effort to distinguish the characteristics of absorbers found in the WHIM phase versus the warm phase, we segment the absorber population by temperature cuts, with a temperature greater than $10^5$ K indicating that the absorber is in the WHIM phase. These absorbers have similar column density distributions as the rest of the population, but $b$-values that are much higher on average. There are no H\textsc{i} (O\textsc{vi}) absorbers in the WHIM phase with $b$-values less than 40 km s$^{-1}$ (10 km s$^{-1}$) by definition, but above those limits the fraction of total absorbers is strongly dominated by WHIM absorbers. These high $b$-value, low column H\textsc{i} absorbers correspond to the population of broad Ly$\alpha$ (BLA) absorbers identified through COS (Danforth et al. 2010) and STIS (Richter et al. 2004, 2006).

There has been substantial recent debate about the origin of O\textsc{vi} absorption line systems, with some work suggesting that it comes entirely from collisional ionization, and other work suggesting that it comes from a combination of collisional and photo ionization. As part of this debate, there has been controversy about the temperature of the plasma where O\textsc{vi} absorption lines predominantly occur. In this work, we investigate the nature of O\textsc{vi} absorbers in the IGM, but take a slightly different approach: we break the absorber population into absorbers dominated by collisional ionization and those dominated by photo ionization, and compare their thermal phase-space properties and column density distributions. We find that the two populations have similar ranges of column densities, but (perhaps unsurprisingly) have bimodal distributions in both temperature and $b$-value.

To investigate the correlation between H\textsc{i} and O\textsc{vi} and the phases of gas that they trace, we find the associated O\textsc{vi} column densities for regions identified as H\textsc{i} absorbers. This shows a marked distinction between the column of associated O\textsc{vi} by column density and $b$-value of H\textsc{i} for the two phases, WHIM and warm, defined as having temperatures greater than and less than $10^5$ K respectively. The WHIM phase has a much higher median column density of associated O\textsc{vi} in all regimes except the highest column H\textsc{i} absorbers. This is consistent with the idea that the WHIM is effectively traced by BLAs, as well as by O\textsc{vi}.

Finally, in consideration of the product $(Z/Z_\odot)f_{O\textsc{vi}}$, we find a much lower average value than the literature standard, comparable with that found by Shull et al. (2012). This may significantly affect predictions of IGM metallicity that have been primarily based on O\textsc{vi} absorption.

6. SUMMARY

In this paper, we compare two primary methods for finding IGM absorbers along lines of sight cast through a simulation box. One method (the “spectral method”) uses synthetic absorption line spectra, and is meant to directly correspond to observational attempts to find structure through fitting Voigt profiles to variations in flux. The other primary method (the “contour method”) relies on defining absorbers by associating contiguous regions along the line of sight based on a threshold number density of the species of interest. After comparing these methods to each other, we compare to observational data of H\textsc{i} and O\textsc{vi} absorption line systems. The key results of this paper are as follows:

1. The two methods give comparable column densities for a given absorber, although there is some difficulty in creating a one-to-one correspondence of absorbers between the two methods. The primary issue for comparing absorbers generated with the two methods appears to be how one decides whether an absorber is a single coherent structure or a complex.

2. The number of H\textsc{i} and O\textsc{vi} absorbers per column density per unit redshift, or $dN/dz$, traced by the two methods give similar results, indicating that the two methods find similar amounts of overall baryons in these ionization states regardless of the ability to match each individual absorber. H\textsc{i} $dN/dz$ compares favorably to observation, while the O\textsc{vi} $dN/dz$ in our simulation underpredicts the observational results. This is likely a shortcoming of the simulation itself, as the abundance of OVI depends sensitively on the assumptions of star formation, feedback, and metal transport.

3. The distribution of Doppler parameters (or $b$-values) by column density in our simulations are similar using the contour and spectral methods in both Ly$\alpha$ and O\textsc{vi}. Both methods of extracting $b$-values from our simulation match observations of Ly$\alpha$ systems as a function of column density. Neither method provides a particularly good fit for the Doppler parameters measured in observed O\textsc{vi} systems; we speculate that this is due to our choice stellar feedback algorithms.

4. The distribution of O\textsc{vi} absorbers over baryon overdensity and temperature was found to be similar to a previous analysis of the same simulation data, but we do not see evidence for a bimodality in absorber distribution by temperature. Instead, we see that O\textsc{vi} absorbers are distributed smoothly in temperature-space from $4.5 < \log(T/K) < 5.5$. 


5. Using the contour method, we find that the relationship between linear size and column density for a given absorber scales as $L \propto N^{-0.12}$, rather than the analytically predicted exponent $-1/3$. The reason for this is unclear, though we speculate that it may be related to simulation resolution or physics.

6. We examine the individual properties of warm versus WHIM tracing HI and O VI absorbers (warm versus WHIM having temperatures greater and less than $10^5$ K respectively) as well as photo- versus collisional ionization dominated O VI absorbers. HI warm/WHIM-tracing absorbers show slightly different column density distributions with number of WHIM absorbers of a given column density falling off much more sharply than number of warm absorbers after $N_{\text{HI}} \sim 10^{14}$ cm$^{-2}$. O VI show similarly shaped column density distributions, albeit with different normalizations. HI and O VI absorbers associated with WHIM gas have systematically higher $b$-values. HI and O VI absorbers associated with warm gas have $b$-value distributions centered around 12 and 10 km s$^{-1}$, respectively, while HI and O VI absorbers associated with the WHIM have $b$-value distributions centered around 45 and 20 km s$^{-1}$. Dividing O VI absorbers into photoionized and collisionally ionized populations shows a similar results to the warm/WHIM division.

7. We investigate the association of warm and WHIM-tracing HI absorbers with O VI absorbers. For HI absorbers emanating from warm gas, there is a positive correlation between HI column density and volume density of associated O VI. Higher column density warm HI absorbers tend to be associated with higher column density O VI absorbers. Comparatively, low column density WHIM-tracing HI absorbers are associated with higher column density O VI absorbers than the warm-tracing HI. However, there does not exist such a trend of increasing O VI column density with increasing HI column density. Instead, the average associated O VI column density peaks at $\sim 10^{13}$ cm$^{-2}$ at an HI column density of $\sim 10^{14}$ cm$^{-2}$.

8. Finally, we study the relation between the column density of O VI absorbers and the value of $(Z/Z_\odot) \times f_{\text{OVI}}$, finding that $f_{\text{OVI}} \propto (N_{\text{OVI}}/(10^{14}$ cm$^{-2}))^{0.7}$. Over the column density range $13 \leq \log N_{\text{OVI}}/\text{cm}^{-2} \leq 15$ this yields an average value of $(Z/Z_\odot) \times f_{\text{OVI}} \approx 0.007$, in reasonable agreement with Shull et al. (2012), but nearly a factor of three lower than earlier estimates. This would imply that O VI traces roughly triple the number of baryons previously thought.

In subsequent papers we hope to expand our analysis of the systematic differences in the contour and spectral methods, and use the nearly one-to-one correlation between the two sets of absorbers to better understand the correspondence between properties of absorption line systems to features in physical structure. We also intend to look at the effects of noise, as well as line blanketing when fitting multiple ions together.

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