AN O VI BARYON CENSUS OF THE LOW-\(z\) WARM-HOT INTERGALACTIC MEDIUM

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ABSTRACT

Intergalactic absorbers along lines of sight to distant quasars are a powerful diagnostic for the evolution and content of the intergalactic medium (IGM). In this study, we use the FUSE satellite to search 129 known Ly\(\alpha\) absorption systems at \(z < 0.15\) toward 31 AGN for corresponding absorption from higher Lyman lines and the important metal ions O VI and C III. We detect O VI in 40 systems over a smaller range of column density (log \(N_{\text{OVI}}\) = 13.0–13.5) than seen in H I (log \(N_{\text{HI}}\) = 13.0–16.0). The co-existence of O VI and H I suggests a multiphase IGM, with warm photoionized and hot ionized components. With improved O VI detection statistics, we find a steep distribution in O VI column density, \(dN_{\text{OVI}}/dN_{\text{OVI}} \propto N_{\text{OVI}}^{-2.75 \pm 0.1}\), suggesting that numerous weak O VI absorbers contain baryonic mass comparable to the rare strong absorbers. Down to 30 mA equivalent width (O VI \(\lambda 1032\)) we find an upper limit on the O VI detection frequency \(dN_{\text{OVI}}/dz \approx 17 \pm 3\). The total cosmological mass fraction in this hot gas is at least \(\Omega_{\text{WHIM}} = (0.0022 \pm 0.0003) [h_0/0.7] (Z_O/0.7Z_\odot) (f_{\text{OVI}}/0.2)^{-1}\) where we have scaled to fiducial values of oxygen metallicity, O VI ionization fraction, and Hubble constant. Gas in the WHIM at 10\(^{5.5}\)–10\(^{7}\) K contributes at least 4.8 \(\pm 0.9\)% of the total baryonic mass at \(z < 0.15\). We then combine empirical scaling relations for the observed “multiphase ratio”, \(N_{\text{HI}}/N_{\text{OVI}} \propto N_{\text{OVI}}^{0.9 \pm 0.1}\), and for hydrogen overdensity in cosmological simulations, \(N_{\text{HI}} \propto \delta_{\text{HI}}^7\), with the H I photoionization correction to derive the mean oxygen metallicity, \(Z_O \approx (0.09Z_\odot)(f_{\text{OVI}}/0.2)^{-1}\) in the low-\(z\) multiphase gas. Given the spread in the empirical relations and in \(f_{\text{OVI}}\), the baryon content in the O VI WHIM could be as large as 10%. Our survey is based on a large improvement in the number of O VI absorbers (40 vs. 10) and total redshift pathlength (\(\Delta z \approx 2.2\) vs. \(\Delta z \approx 0.5\)) compared to earlier surveys.

Subject headings: cosmological parameters—cosmology—observations—intergalactic medium—quasars: absorption lines

1. INTRODUCTION

One of the great, unanticipated legacies of the Far Ultraviolet Spectroscopic Explorer (FUSE) mission is surely the detection of O VI absorption lines along extragalactic sight lines from the warm-hot intergalactic medium (WHIM) at \(T = 10^5–10^7\) K, as predicted by cosmological simulations (Cen & Ostriker 1999; Davé et al. 2001). Hot gas in the intergalactic medium (IGM) is produced by shocks generated by gravitational instability during galaxy formation. The O VI absorption lines are formed in highly ionized oxygen, which has been shock-heated to temperatures of several \(10^5–10^6\) K, somewhat cooler than the bulk of the WHIM, which has been shock-heated to temperatures of several \(10^6\) K. This latter, very hot gas is only detectable by shocks generated by gravitational instability during galaxy formation. The O VI absorption lines are an indicator of widespread multiphase IGM, with warm photoionized and hot ionized components.

The search for the WHIM gas has now begun in earnest, using sensitive UV resonance absorption lines, primarily the O VI doublet (1031.926, 1037.671 Å) which is \(\approx 100\) times more sensitive than the X-ray transitions of O VII (21.602 Å) or O VIII (18.97 Å). Thus, the initial WHIM detections of O VI were made by FUSE at \(z \leq 0.15\) and by the Hubble Space Telescope (HST) at \(z \geq 0.12\), but over a modest total redshift pathlength \(\Delta z \approx 0.5\) (Tripp, Savage, & Jenkins 2000, Savage et al. 2002). For the portion of WHIM containing O VI, the estimated baryon fractions were \(\approx 5%\) for O/H metallicity equal to 10% of the former solar value, \(7.41 \times 10^{-4}\) (Grevesse et al. 1996). Because the solar oxygen abundance has recently been re-measured at (O/H)\(_\odot\) = 4.90 \(\times 10^{-4}\) (Allende Prieto et al. 2001), we have re-scaled our baryon estimates to this lower value. These estimates have large uncertainties, including untested assumptions of uniform metallicity, O VI ionization equilibrium, and multiphase IGM structure.

The initial O VI searches reported only a handful of absorbers – four systems by Tripp, Savage, & Jenkins 2000 and six by Savage et al. 2002. At low redshift, down to 50 mA equivalent width in O VI \(\lambda 1032\), the number of O VI absorbers per unit redshift is 10–15% of that found in the H I Ly\(\alpha\) surveys: \(dN_{\text{OVI}}/dz \approx 14_{-9}^{+14}\) (Savage et al. 2002) versus \(dN_{\text{HI}}/dz \approx 112_{-9}^{+14}\) (Penton, Stocke, & Shull 2004). In this study, we dramatically increase the total surveyed pathlength to \(\Delta z > 2\) and the total number of O VI absorbers to 40. We also study the relationship between absorbers from the WHIM and the warm neutral medium (WNM; \(10^3–4\times 10^4\) K). With the increased number of absorbers, we can begin to look at WHIM absorption in a statistical manner, particularly the distribution in O VI column density.

2. OBSERVATIONS AND DATA ANALYSIS

\footnote{1 also at JILA, University of Colorado and National Institute of Standards and Technology}
We began our survey with published lists of intervening Lyα absorption systems toward low-$z$ AGN obtained from GHRS and STIS surveys by Penton, Shull, & Stocke (2000); Penton, Stocke, & Shull (2004). Other sight lines were covered by literature sources or measured at the University of Colorado from STIS/E140M spectra as discussed in the upcoming Danforth, Shull, & Rosenberg (2005, hereafter Paper II). We disregarded any weak Lyα absorbers (W_α < 80 mA, log N_H ≲ 13.2) and searched the FUSE data for higher-order Lyman lines plus O VI and C III counterparts. We have been conservative in our identification of O VI systems, requiring unambiguous ($≥4σ$) features, and examining multiple channels of FUSE data and both lines of the O VI doublet when possible. In all, we analyzed 171 absorbers in 31 FUSE sight lines. We measured all available Lyman series lines to determine accurate N_H and doppler b values for H I via curve-of-growth concordance curves (Shull et al. 2000).

Of the Lyα absorbers, 129 were at $z ≤ 0.15$, where O VI absorption could potentially be observed. We detected O VI at $4σ$ or greater level in one or both lines of the doublet for 40 absorbers, and we obtained $4σ$ or greater upper limits in 84 other cases. The remaining five absorbers fell on top of airglow or strong lines from the interstellar medium (ISM), were blended, or were in some other way inaccessible.

We determined metal-ion column densities via Voigt profile fits and/or the apparent column method of Savage & Sembach (1991). We assumed that any saturation in these lines was mild, and that profile fits accurately determine the column density. In cases where we detected both O VI lines, we assigned a weighted mean of the column densities to N_OVI. We describe the full details of absorber selection and data analysis in Paper II.

3. THE MULTIPHASE IGM

The O VI lines are ideal tracers (at $10^{5.5±0.3}$ K) for the warm-hot ionized medium (WHIM; $10^5−10^7$ K), while H I traces the photoionized warm neutral medium (WNM; $10^{3.5−4.5}$ K). The left panel of Figure 1 shows a weak correlation, if any, between N_OVI and N_H. While N_H varies over nearly three orders of magnitude, N_OVI is detected between $10^{13}$ cm$^{-2}$ and a few times $10^{14}$ cm$^{-2}$ (a factor of $~20$). To gauge the relative amounts of warm photoionized gas (H I) and hot collisionally ionized gas (O VI), we use the “multiphase ratio”, N_H/N_OVI. This ratio was defined previously as a means of assessing the range in contributions from photoionized gas (H I) and collisionally ionized gas (O VI), which often appear to be associated kinematically (Sembach et al. 2003; Collins, Shull, & Giroux 2004).

As shown in the right panel of Figure 1, the N_H/N_OVI ratio exhibits a strong correlation with N_H, with a typical range N_H/N_OVI $≈ 0.5$–$50$ and a dispersion of less than one (dex). Higher H I column absorbers typically display a higher multiphase ratio, while weak H I absorbers have N_OVI $≈ (0.1−2)$N_H. We are well aware of the fact that plots such as Figure 1 are subject to the effects of correlated errors in N_H. However, this ratio has physical utility in deriving a mean (O/H) metallicity in multiphase gas (see § 4), when combined with the empirical correlation between N_H and hydrogen overdensity, δ_H, seen in cosmological simulations (Dave et al. 1999).
a combination of external ionizing photons (from AGN), shocks from infalling clouds, and possible shocks from cluster outflows such as superwinds and SNR feedback. The narrow range of \( N_{\text{OVII}} \) compared to \( N_{\text{HI}} \) implies that the WHIM shell may have a characteristic column density of \( 10^{13} - 10^{14} \text{ cm}^{-2} \), while the neutral core can be arbitrarily large.

In this scenario, the very large values of the multiphase ratio may arise in “quiescent gas”, possibly located in high-column density H I gas in halos. The absence of associated O VI suggests the lack of shocks at velocities greater than about 150 km s\(^{-1}\). Many strong H I (Ly\(\alpha\)) absorbers have been seen in proximity (within 200 h\(^{-1}\) kpc) of bright galaxies (Lanzetta et al. 1995; Chen et al. 1995; Penton, Stocke, & Shull 2003). In our current O VI sample, we found three absorbers with extremely high multiphase ratios: very high neutral hydrogen columns with no detectable WHIM. In the first case, the absorber at \( c_z = 1586 \text{ km s}^{-1} \) toward 3C273 shows \( \log N_{\text{HI}} = 15.67 \) and \( \log N_{\text{OVII}} \leq 13.17 \) and is \( 71 h^{-1} \text{ kpc} \) on the sky from a dwarf (\( M_B = -13.9 \)) post-starburst galaxy (Stocke et al. 2004). The second case is the absorber at \( c_z = 23,688 \text{ km s}^{-1} \) toward PHL 1811 with \( \log N_{\text{HI}} = 15.94 \) and \( \log N_{\text{OVII}} \leq 13.06 \). This system is beyond the \( L^* \) survey depth, so we cannot comment on surrounding galaxies. Finally, the Lyman-limit system at \( c_z = 24,215 \text{ km s}^{-1} \) toward PHL 1811 shows \( \log N_{\text{HI}} = 18.11 \) and \( \log N_{\text{OVII}} \leq 13.06 \). This absorber lies \( 23'' (34 h^{-1} \text{ kpc}) \) from an \( L^* \) galaxy at \( z = 0.0808 \) (Jenkins et al. 2003). Tripp et al. (2005) note a sub-DLA system at \( z_{\text{abs}} = 0.00632 \) toward PG 1216+069 with \( \log N_{\text{HI}} = 19.32 \) and \( \log N_{\text{OVII}} \leq 14.3 \) which lies 86 kpc from a sub-L* galaxy. These four absorption systems, with multiphase ratios \( \log [N_{\text{HI}}/N_{\text{OVII}}] \geq 2.5, 2.9, 5.0, \) and 5.0 respectively, may be shielded from external ionizing flux by adjacent IGM clouds and have unshocked gas.

Metallicity is one of the great unknowns in interpreting the baryon content of the WHIM absorbers. In previous studies, \( (O/H) \) has been assumed to be constant at 10% solar. However, one might expect that metallicity variations could play a role in the multiphase ratio: outflows of material from galaxies should be denser and more enriched than primordial IGM clouds. This would contribute a negative slope in the multiphase ratio plot. Some absorbers at lower metallicity. While metallicity variations almost certainly exist in the IGM, they are not the main cause of the positive slope in the multiphase ratio plot. Some of this effect could arise from changes in the mean O VI ionization fraction, typically chosen to be the maximum value, \( f_{\text{OVII}} \approx 0.2 \) at \( T_{\text{max}} = 10^5-10^6 \text{ K} \) in collisional ionization equilibrium (Sutherland & Dopita 1993). This fraction is expected to vary, depending on the range of shock velocities that produce the O VI (Heckman et al. 2002; Rajan & Shull 2005).

4. THE HOT BARYON CONTENT OF THE UNIVERSE

Using O VI as a tracer of the \( 10^{6-8} \text{ K} \) portion of the WHIM, we can employ the number of absorbers per unit redshift, \( dN_{\text{OVII}}/dz \), to determine \( \Omega_{\text{WHIM}} \), the fraction of the critical density contributed by this WHIM gas. Our detection statistics are shown in Figure 2 for O VI.

The total redshift pathlength of our survey is a function of equivalent width, and our survey is more complete for strong absorbers than for weak absorbers. The equivalent-width sensitivity, \( W_{\text{min}} (\lambda) \), is a function of spectrograph resolution, \( R = \lambda/\Delta \lambda \), and the signal-to-noise ratio \( (S/N) \) of the data per resolution element. Thus, for a 4\( \sigma \) detection limit, we define \( W_{\text{min}} (\lambda) = (4/\sqrt{S/N})(S/N) \). We assume \( R = 20,000 \) and calculate \( W_{\text{min}} \) profiles for each dataset based on \( S/N \) measured every 10 A. Strong instrumental features, ISM absorption, and airglow lines are masked out \( (S/N \) set to zero). From this procedure, we calculate \( \Delta z \) as a function of \( W_{\text{min}} (\lambda) \) for both O VI transitions, using curves of growth with \( \Delta z \). By moving an absorber doublet along the profile as a function of \( z_{\text{abs}} \), we generate a profile \( \Delta z \). By adding up the total path length for each absorber at each \( \Delta z \), we determine the relationship between \( N_{\text{OVII}} \) and \( \Delta z \) as shown in Figure 3. With a total high-\( N_{\text{OVII}} \) pathlength \( \Delta z = 2.2 \), we are at least 80% complete in O VI detection down to \( \log N_{\text{OVII}} = 13.4 \) \( (W_{\lambda} = 30 \text{ mA} \) in the 1032 A line). However, \( \Delta z \) and the completeness fall off rapidly for weaker absorbers. Dividing Figure 2 by Figure 3, we obtain the profile of \( dN_{\text{OVII}}/dz \) as a function of \( N_{\text{OVII}} \) (Figure 4). To first order, this procedure should correct for incompleteness in our O VI survey.

Our incompleteness-corrected value of the absorber frequency, \( dN_{\text{OVII}}/dz \), compares well with previous, uncorrected values (Table 1). For O VI absorbers with \( W_{\lambda} \geq 50 \text{ mA} \) (in \( \lambda_{1032} \)), we find \( dN_{\text{OVII}}/dz = 9 \pm 2 \), somewhat lower than the value, \( dN_{\text{OVII}}/dz = 14^{+6}_{-9} \), found by Savage et al. (2002) using six O VI absorbers toward PG0953+415. For the weaker O VI absorbers, we find \( dN_{\text{OVII}}/dz = 17 \pm 3 \) \( (W_{\lambda} \geq 30 \text{ mA}) \) and \( dN_{\text{OVII}}/dz = 19 \pm 3 \) \( (W_{\lambda} \geq 15 \text{ mA}) \) from our total sample of 40+ measured O VI absorbers. Uncertainties are based on single-sided 1\( \sigma \) confidence limits in Poisson statistics (Gehrels 1986). Tripp, Savage, & Jenkins (2000) found

![Figure 2](image-url)
\[ \frac{dN_{\text{OVI}}}{dz} > 17 \text{ at 90\% confidence for } \lambda_{\text{abs}} \geq 30 \text{ m\AA}, \]
based on four absorbers toward H1821+643.

A recent study (Tripp et al. 2004) using STIS/E140M data finds \( \frac{dN_{\text{OVI}}}{dz} = 23 \pm 4 \) for \( \lambda_{\text{abs}} \geq 30 \text{ m\AA} \) based on 44 O VI absorbers. This sample was taken at higher redshift (0.12 \( \leq z_{\text{abs}} \leq 0.57 \)) than our sample (\( z_{\text{abs}} \leq 0.15 \)) and shows a higher value of \( \frac{dN_{\text{OVI}}}{dz} \). This is not predicted by simulations, which predict an increasing WHIM fraction at recent epochs. However, the difference in redshift between the two samples is small, and the discrepancy in \( \frac{dN_{\text{OVI}}}{dz} \) may be a result of cosmic variance.

Recent cosmological simulations of the X-ray forest predict a distribution of O VI absorbers and provide a convenient way to check current simulations with observed data. Chen et al. (2003) model the X-ray forest assuming a ΛCDM model similar to Dave et al. (2001), both collisional ionization and photoionization from a UV background, radiative cooling, and a range of different metallicities. The cumulative distribution of O VI absorbers (\( \frac{dN_{\text{OVI}}}{d\ln[1+z]} \)) down to a minimum equivalent width is drawn from these models and provides a convenient comparison with observed statistics from our work and previous surveys (see Figure 5).

The simulation with \( Z = 0.1 \text{Z}_\odot \) shows a reasonably good match to the observed cumulative distribution of O VI absorbers in the local universe. Weaker absorbers (\( \lambda_{\text{abs}} < 30 \text{ m\AA} \)) are overpredicted compared with observations, but this may be a matter of small-number statistics or differing detection thresholds between observations and simulations. A simulation in which metallicity is a function of overdensity fits the data slightly better than the fixed-metallicity model. However, Chen et al. (2003) caution that there is a substantial scatter in the simulations, so that the lower-metallicity curves are essentially indistinguishable. The \( Z = 0.5 \text{Z}_\odot \) model of Fang, Bryan, & Canizares (2002) also fits the observed data reasonably well, but it is based on a less physical simulation with no photoionization and no radiative cool-
increasing. The solar metallicity model of the IGM can clearly be ruled out by our observations. Simulations at lower metallicities ($Z = 0.01 Z_\odot$) would be helpful, given the wealth of new observational results.

From $dN/dz$, we can calculate the contribution to $\Omega_h$ from WHIM gas, as discussed in Savage et al. (2002). We assume a Hubble constant $H_0 = 70h_{70}$ km s$^{-1}$ Mpc$^{-1}$, rather than their value $h_{75}$, and we make standard assumptions regarding O VI ionization fraction and (O/H) metallicity (Tripp, Savage, & Jenkins 2002; Savage et al. 2002). We adopt an ionization fraction, $f_{\text{OVI}} = 0.2$ characteristic of its maximum value in collisional ionization equilibrium (CIE) and assume an O/H abundance 10% of the solar value. Of course, CIE is almost certainly not a valid assumption for the low-density IGM. As the infalling gas is shock-heated during structure formation, the ionization states O VI, O VII, and O VIII undergo transient spikes in abundance, followed by cooling and recombination. Recent time-dependent models of the ionization, recombination, and cooling of shock-heated, low-density WHIM (Rajan & Shull 2005) find that the mean, time-averaged O VI ion fraction is $f_{\text{OVI}} = 8-35\%$, over a range of initial temperatures $5.4 \leq T \leq 6.2$. These fractions are compatible with (a factor of two spread) with the fiducial value, $f_{\text{OVI}} = 0.2$, based on the maximum fraction of O VI at $T_{\text{max}} = 10^{5.45}$ K, in CIE (Sutherland & Dopita 1993).

As shown above (Fig. 5), a metallicity $Z = 0.1 Z_\odot$ is reasonably consistent with the observed equivalent width distribution of O VI absorbers at $z \sim 0$. However, using our sample of O VI and H I absorbers, we can make a more direct estimate of the (O/H) metallicity. To do so, we must estimate the amount of hydrogen associated with each component of the multiphase system of photoionized H I and collisionally ionized O VI. Since the H I and O VI absorbers are associated kinematically, we assume they share the same metallicity. We then use the empirical relations between $N_{\text{HI}}$ and overdensity, $\delta_H$, and between the multiphase ratio ($N_{\text{HI}}/N_{\text{OVI}}$) and $N_{\text{HI}}$, and

$$\delta_H \equiv \frac{n_H}{(1.90 \times 10^{-7} \text{ cm}^{-3}) (1+z)^3} \approx 20 N_{14}^{0.7} 10^{-0.4z}.$$ \hspace{1cm} (2)

The above relations allow us to relate $N_{\text{HI}}$ to the physical gas density, $n_H$, needed for the hydrogen photoionization correction. Equation (1) is derived by fitting the multiphase correlation in Fig. 1b over the approximate range $10 \leq \delta_H \leq 300$. The scaling constant $C_0 = 2.5 \pm 0.2$ is the mean multiphase ratio at log $N_{\text{HI}} = 14$, and the best-fit slope is $\alpha = 0.9 \pm 0.1$. Equation (2) comes from cosmological simulations (Davé et al. 1999) and relates the hydrogen overdensity, $\delta_H$, to the H I column density, $N_{\text{HI}} \geq 10^{14} \text{ cm}^{-2}$.

From these relations, we can derive a statistical value of the (O/H) metallicity from the formula,

$$\langle N_{\text{O}}/N_{\text{H}} \rangle = \langle N_{\text{OVI}}/N_{\text{HI}} \rangle \times \left( \frac{f_{\text{HI}}}{f_{\text{OVI}}} \right).$$ \hspace{1cm} (3)

We employ the multiphase ratio, $N_{\text{HI}}/N_{\text{OVI}}$, together with appropriate ionization correction factors, $f_{\text{OVI}}$ and $f_{\text{HI}}$. The H I fraction is derived from photoionization equilibrium in the low-$z$ IGM

$$f_{\text{HI}} = \frac{n_e \alpha_{\text{H}}}{\Gamma_H} = (1.80 \times 10^{-5}) (1+z)^3 \left( \frac{\delta_H}{20} \right) T_{4}^{-0.726} \Gamma_{-13}^{-1},$$ \hspace{1cm} (4)

for gas with $n_e = 1.16 n_H$ at temperature ($10^{4}$ K)$T_{4}$, photoionized at rate $\Gamma_H = (10^{-13} \text{ s}^{-1}) \Gamma_{-13}$. Since the mean-free path of a Lyman continuum photon is very large in the low-overdensity IGM, we use the case-A recombination rate coefficient $\alpha_{\text{H}}^{(A)} = (4.0 \times 10^{-13} \text{ cm}^3 \text{s}^{-1}) T_{4}^{-0.726}$. Combining the two empirical relations with the relation of photoionization equilibrium, we find that the mean oxygen metallicity of the O VI absorbers at $z = 0.06$ is

$$Z_O = (0.09 Z_\odot) N_{14}^{-0.2} T_{4}^{-0.726} \Gamma_{-13}^{-1} \left( \frac{f_{\text{OVI}}}{0.2} \right)^{-1}.$$ \hspace{1cm} (5)

Given the uncertainties in these empirical relations, it is remarkable that this formula arrives at an oxygen abundance near the fiducial value of 10% solar. In fact, our estimated value, $Z_O = 0.09 Z_\odot$, is probably accurate to only a factor of 2.

### Table 1: IGM O VI Absorber Statistics

| Criteria | $N_{\text{abs}}$ | $dN/dz$ | $\omega_{\text{WHIM}}$$^a$ | Reference |
|----------|-----------------|--------|-----------------------------|-----------|
| $W \geq 10$ mA | 40 | $21 \pm 3$ | 0.0022 $\pm$ 0.0003 | this work |
| $W \geq 15$ mA | 38 | $19 \pm 3$ | 0.0021 $\pm$ 0.0003 | this work |
| $W \geq 30$ mA | 35 | $17 \pm 3$ | 0.0021 $\pm$ 0.0004 | this work |
| $W \geq 50$ mA | 19 | $9 \pm 2$ | 0.0016 $\pm$ 0.0005 | this work |
| $W \geq 100$ mA | 6 | $3.1^{+2}_{-1}$ | 0.0008 $\pm$ 0.0004 | this work |
| $W \geq 30$ mA | 44 | $23 \pm 4$ | 0.0027 | Tripp et al. (2004) |
| $W \geq 50$ mA | 4 | $17 >0.006$$^b$ | Tripp, Savage, & Jenkins (2002) |
| $W \geq 50$ mA | 6 | $14^{+9}_{-6}$ | $>0.003$ | Savage et al. (2002) |

$^a$All $\omega_{\text{WHIM}}$ values have been converted to a consistent set of $f_{\text{OVI}} = 0.2, Z = 0.1 Z_\odot, H_0 = 70h_{70}$ km s$^{-1}$ Mpc$^{-1}$, and $\langle O/H \rangle = (4.0 \times 10^{-13} \text{ cm}^3 \text{s}^{-1}) T_{4}^{-0.726}$.

$^b$All four O VI absorbers in Tripp, Savage, & Jenkins (2002) lie along the unusually rich H1821+643 sight line.
We now derive the fractional contribution to closure density of WHIM baryons associated with hot O VI,

\[
\Omega_{\text{WHIM}} = \left( \frac{H_0}{c_{\text{pcr}}} \right) \frac{\mu m_H}{(O/H)_{\odot}} Z f_{\text{OVI}} \\
\times \int_{N_{\text{min}}}^{N_{\text{max}}} \left( \frac{dN}{dz} \right) \langle N_{\text{OVI}} \rangle dN_{\text{OVI}} \\
= (1.85 \times 10^{-18}) \ h_70^{-1} \sum_i \left( \frac{dN}{dz} \right)_i \langle N_{\text{OVI}} \rangle_i.
\]

We perform the above sum using the value, \((dN/dz)_i\), for each column-density bin in Figure 4, with \(\langle N_{\text{OVI}} \rangle_i\) chosen as the mean column density (cm\(^{-2}\)) in the bin. We find \(\Omega_{\text{WHIM}} = (0.0022 \pm 0.0003)h_7^{-1}\). Values of \(\Omega_{\text{WHIM}}\) for other equivalent width thresholds are listed in Table 1 along with the results of other studies converted to uniform values of \(H_0, f_{\text{OVI}},\) and \((O/H)_{\odot}\).

It should be stressed that these estimates of \(\Omega_{\text{WHIM}}\) are based on an assumed uniform 10% solar (O/H) metallicity and that further uncertainty arises in our assumed O VI ionization fraction. Changes in \(f_{\text{OVI}}\) within the range of mean values \(\langle f_{\text{OVI}} \rangle\) could change our result by a factor of two. Based on the standard assumptions, our result is slightly lower than the result published by Savage et al. (2002), where \(\Omega_{\text{WHIM}} \geq 0.002h_7^{-1}\). Savage et al. (2002) used an older solar oxygen abundance, \((O/H)_{\odot} = 7.41 \times 10^{-4}\), which is 50% larger than the Allende Prieto et al. (2001) value. After correcting for this difference, their result for \(\Omega_{\text{WHIM}}\) is larger than ours. Tripp et al. (2004) find \(\Omega_{\text{WHIM}} = 0.027\) based on 44 absorbers at \(z \geq 0.12\).

Our estimate corresponds to \(\Omega_{\text{WHIM}}/\Omega_b = 0.048 \pm 0.007\), so that WHIM gas in the range \(10^{6-7}\) K makes up roughly 5% of the baryonic mass in the local universe. The contribution could exceed 10% if we account for the likely spread in (O/H) metallicities and O VI ionization fractions. Predictions that the current universe is composed of \(\sim 30\%\) WHIM gas, so our value of \(\sim 3 - 10\%\) falls short of this mark. However, O VI is only useful as a proxy for gas within the lower portion of the WHIM temperature range. Accounting for the hotter \(10^{6-7}\) K gas using similar methodology will require high-sensitivity, high resolution X-ray observations of O VII and O VIII with spectrometers aboard future missions such as Constellation-X or XEUS (Fang, Bryan, & Canizares 2002, Chen et al. 2003). Limited observational work has been done in this area (Nicasio et al. 2003), but the current generation of X-ray telescopes are not ideal for this kind of investigation.

The distribution of H I absorbers with column density is often expressed as a power law with index \(\beta\): \(dN/dN \propto N^{-\beta}\) (Wevmann et al. 1998, Penton, Stocke, & Shull 2002, 2004). For the first time, this analysis can be applied to WHIM species. We find that the differential number of O VI absorbers with column density is a power law, \(dN_{\text{OVI}}/dN_{\text{OVI}} \propto N_{\text{OVI}}^{-2.2 \pm 0.1}\) for absorbers with \(\log N_{\text{OVI}} \geq 13.4\). This is somewhat steeper than the corresponding H I distribution, \(\beta \sim 1.6\) (Penton, Stocke, & Shull 2004) and means that low-column absorbers contribute comparable amounts to the O VI baryon census as the rare high-column systems. Note that in eq. [6], \(\Omega_{\text{WHIM}}\) scales as \(N_{\text{OVI}}^{-0.2}\) for \(\beta = 2.2\). Even though we correct for incompleteness in the weaker absorbers, the statistics are still poor at \(\log N_{\text{OVI}} \leq 13.4\). It is unclear whether the turnover in \(dN_{\text{OVI}}/dz\) at lower columns is real or a statistical fluctuation from small numbers of weak absorbers. Nevertheless, the weak O VI absorbers appear to make significant contributions to the baryon mass density. The steep power law also reinforces our conclusions about the nature of the multiphase IGM with a core-halo structure.

We have demonstrated that the contributions from weak O VI absorbers cannot be neglected in an accurate WHIM baryon census. The rare strong O VI absorbers and numerous weak absorbers contribute nearly equally to \(\Omega_{\text{WHIM}}\). Further FUSE observations at high-S/N will allow us to probe weak O VI absorbers and refine the statistics at the low-column end of the absorber distribution. An analysis of O VI absorbers at higher redshifts \((z > 0.5)\) would allow us to track changes in the WHIM density, confirming the decrease in the amount of shocked gas at higher redshifts predicted by cosmological simulations (Cen & Ostriker 1999, Davé et al. 1999, 2001).

Only by enlarging our sample of multiphase (H I, O VI) absorbers beyond the 40 discussed here will we be able to refine our statistical estimate for the metallicity of the WHIM. With a much larger sample of O VI absorbers, we could use maximum-likelihood techniques to search for the expected trends: (1) decreasing metallicity at lower overdensity \(\delta_H\) (Gnedin & Ostriker 1997); (2) decreasing \(\Omega_{\text{OVI}}\) at higher redshift (Davé et al. 1999); and (3) trends of \(N_{\text{HI}}/N_{\text{OVI}}\) with other metal indicators such as C III, C IV, or Si IV.

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