THE BARYON CENSUS IN A MULTIPHASE INTERGALACTIC MEDIUM: 30% OF THE BARYONS MAY STILL BE MISSING

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ABSTRACT

Although galaxies, groups, and clusters contain ~10% of the baryons, many more reside in the photoionized and shocked-heated intergalactic medium (IGM) and in the circumgalactic medium (CGM). We update the baryon census in the (H_I) Ly α forest and warm-hot IGM (WHIM) at 10^{5–6} K traced by O vI λ 1032, 1038 absorption. From Enzo cosmological simulations of heating, cooling, and metal transport, we improve the H I and O vI baryon surveys using spatially averaged corrections for metallicity (Z/Z_{\odot}) and ionization fractions ($f_{\rm HI}$, $f_{\rm OvI}$). Statistically, the O vI correction product correlates with column density, $(Z/Z_{\odot}) f_{\rm OvI} \approx (0.015)(N_{\rm OvI}/10^{14} \,{\rm cm}^{-2})^{0.70}$, with an $N_{\rm OvI}$ -weighted mean of 0.01, which doubles previous estimates of WHIM baryon content. We also update the Ly α forest contribution to baryon density out to z = 0.4, correcting for the $(1 + z)^3$ increase in absorber density, the $(1 + z)^{4.4}$ rise in photoionizing background, and cosmological proper length $d\ell/dz$. We find substantial baryon fractions in the photoionized Ly α forest (28% ± 11%) and WHIM traced by O vI and broad-Ly α absorbers (25% ± 8%). The collapsed phase (galaxies, groups, clusters, CGM) contains 18% ± 4%, leaving an apparent baryon shortfall of 29% ± 13%. Our simulations suggest that ~15% reside in hotter WHIM ($T \ge 10^{16}$ K). Additional baryons could be detected in weaker Ly α and O vI absorbers. Further progress requires higher-precision baryon surveys of weak absorbers, down to minimum column densities $N_{\rm HI} \ge 10^{12.0}$ cm⁻², $N_{\rm OvI} \ge 10^{12.5}$ cm⁻², using high signal-to-noise data from high-resolution UV and X-ray spectrographs.

Key words: cosmological parameters - intergalactic medium - quasars: absorption lines

Online-only material: color figures

1. INTRODUCTION

For low-redshift cosmology and galaxy formation rates, it is important to account for all the baryons synthesized in the Big Bang. Cosmologists have noted a baryon deficit in the lowredshift universe (Fukugita et al. 1998) relative to the predicted density synthesized in the Big Bang. Although this deficit could arise from an incomplete inventory, it could also challenge our understanding of the thermodynamics of structure formation and the response of the gas to accretion shocks and galactic outflows. Recent analysis (Komatsu et al. 2011) of the spectrum of acoustic peaks in the cosmic microwave background (CMB) obtained by the Wilkinson Microwave Anisotropy Probe found that baryons comprise a fraction $\Omega_b = 0.0455 \pm 0.0028$ of the critical matter energy density of the universe, $\rho_{cr} = (9.205 \times$ the universe, $\rho_{cr} \equiv (9.205 \times 10^{-30} \text{ g cm}^{-3}) h_{70}^2$, where h_{70} is the Hubble constant (H_0) in units of 70 km s⁻¹ Mpc⁻¹. This 4.6% baryon fraction corresponds to a mean comoving density $\overline{\rho}_b = \Omega_b \rho_{cr} = 4.24 \times 10^{-31} \text{ g cm}^{-3}$ and a hydrogen number density $n_{\rm H} = 1.90 \times 10^{-7} \text{ cm}^{-3}$, assuming a primordial helium mass fraction $Y_p = 0.2477$ (Peimbert et al. 2007).

Unfortunately, the observed baryon inventories in the lowredshift universe are uncertain. Theoretical estimates of the physical state of the gas are complicated by the formation of galaxies and large-scale structure and feedback from star formation in the form of ionizing radiation, metals, and outflows. Galaxy surveys have found $\sim 10\%$ of these baryons in collapsed objects such as galaxies, groups, and clusters (Salucci & Persic 1999; Bristow & Phillipps 1994; Fukugita & Peebles 2004).

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Over the last 15 years, substantial reservoirs of gas have been found in the intergalactic medium (IGM), in the halos of galaxies, and in the circumgalactic medium (CGM). There are often semantic problems in defining the CGM, as gas blown out of galaxies or material within the virial radius (Tumlinson et al. 2011; Prochaska et al. 2011). Of the remaining 80%–90% of cosmological baryons, approximately half can be accounted for in the low-z IGM (Shull 2003; Bregman 2007; Danforth & Shull 2008; Danforth 2009) including the warm-hot IGM (or WHIM). Ultraviolet spectroscopic surveys of $Ly\alpha$ and Oyihave identified substantial numbers of absorbers (Danforth & Shull 2008; Tripp et al. 2008; Thom & Chen 2008), but claimed detections of hotter gas in X-ray absorption by O VII (Nicastro et al. 2005a, 2005b) remain controversial (Kaastra et al. 2006; Yao et al. 2012). Unfortunately, X-ray spectra still have not confirmed the potential large reservoir of baryons at $T > 10^6$ K. suggested by cosmological simulations.

An inefficient distribution of collapsed baryons versus distributed matter is a prediction of nearly all cosmological simulations of large-scale structure formation (Cen & Ostriker 1999, 2006; Davé et al. 1999, 2001; Smith et al. 2011; Tepper-García et al. 2011). These *N*-body hydrodynamical simulations suggest that 10%–20% of the baryons reside in collapsed objects and dense filaments, with the remaining 80% distributed over a wide range of phases in baryon overdensity ($\Delta_b = \rho_b/\overline{\rho}_b$) and temperature (*T*). Thermodynamic considerations suggest that shock-heated WHIM at z < 1 is a natural consequence of gravitational instability in a dark-matter-dominated universe. This hot gas is augmented by galactic-wind shocks and virialization in galaxy halos.

In this paper, we improve the analysis of baryon content in both photoionized and shocked-heated IGM phases and assess the accuracy of observational and theoretical estimates. Because Ly α absorption surveys probe the neutral component of diffuse, photoionized filaments, assessing the baryon content requires a correction for the neutral fraction, $f_{\rm HI}$. We derive more accurate photoionization corrections, both from cosmological simulations and analytic models. The analytic models are updated, accounting for the $(1 + z)^{4.4}$ rise in the metagalactic ionizing background out to $z \approx 0.7$, the $(1 + z)^3$ increase in absorber density, and changes in cosmological proper length, $d\ell/dz$. Our simulations also correct the O vI surveys for ionization fraction ($f_{\rm OvI}$) and metallicity (Z/Z_{\odot}). Finally, we use our critically evaluated catalog (Tilton et al. 2012) of H I and O vI absorption lines from our *Hubble Space Telescope (HST)* Legacy Archive Project on IGM data taken by the *HST* and the *Far-Ultraviolet Spectroscopic Explorer (FUSE*).

To constrain the distribution of Z and $f_{O_{VI}}$, we use cosmological hydrodynamic simulations of IGM heating, cooling, and metal transport to find the column-density-weighted average for their product, $(Z/Z_{\odot}) f_{O_{VI}}$. Whereas previous work assumed constant values, $Z/Z_{\odot} = 0.1$ and $f_{O_{VI}} = 0.2$, our new simulations provide spatially averaged corrections for metallicity, O vi ionization fraction, and covariance of IGM parameters (T, T) ρ , Z). Our computed mean value $\langle (Z/Z_{\odot}) f_{O_{VI}} \rangle = 0.01$ is half the previously assumed value, thereby doubling previous estimates of the baryon census traced by Ovi. In Section 2, we describe the simulations and their results for the Ovi distribution in column density, gas temperature, baryon overdensity, metallicity, and ionization fraction. In Section 3, we assess the corrections for ionization and metallicity, applied to the O VI and Ly α absorbers, and we derive values of Ω_b from recent surveys of IGM and CGM phases. Variations in these factors are produced by WHIM thermodynamics, gas temperature (T), baryon overdensity (Δ_b) , and O vI column density $(N_{O vI})$. In Section 4, we summarize the current baryon census with uncertainties on each component. Our conclusions and recommendations for future work are given in Section 5.

2. COSMOLOGICAL SIMULATIONS OF THE WHIM

The primary simulation analyzed in this work is run 50_1024_2 of Smith et al. (2011) with "distributed feedback" implemented with the adaptive-mesh refinement (AMR) + N-body code Enzo (Bryan & Norman 1999; O'Shea et al. 2005a). To check convergence and robustness of our results, we also looked at run 50_1024_1 with "local feedback." The simulations have a box size of $50 h^{-1}$ Mpc comoving, with 1024^3 grid cells and dark matter particles, yielding a dark matter mass resolution of $7 \times 10^6 M_{\odot}$ and spatial cells of 49 h^{-1} kpc (comoving). We have employed a sophisticated treatment of metal cooling and heating (Smith et al. 2008, 2011). Radiative cooling is included by solving for the non-equilibrium chemistry and cooling of atomic H and He, coupled to tabulated metal cooling rates computed as a function of density, metallicity, temperature, electron fraction, and redshift in the presence of an ionizing metagalactic radiation background. To mimic the effects of reionization, we included a spatially uniform, but redshift-dependent radiation background given by Haardt & Madau (2001). The radiation background influences the gas through photoheating and photoionization, whose effects are included in the cooling of both the primordial and metal species.

The spatial and temporal injection of feedback is governed by the rate at which thermal energy and metals are placed into the grid by star particles. A major difference between our metal injection and that used by Oppenheimer & Davé (2009) is the degree of metal mixing. In their smoothed particle hydrodynamics (SPH) formulation, Oppenheimer and Davé inject unmixed metals into a "particle," using a galactic-wind formulation. In our grid code, described below and in Smith et al. (2011), the metals are injected along with mass and energy, distributed in both space and time, and assumed to be fully mixed. Mass and energy are either placed into a single cell ("local feedback") or 27 cells ("distributed feedback"). The subsequent metal transport is achieved by pressure gradients across cells, rather than by explicit addition of kinetic energy by galactic winds. Our standard results are based on the distributed method. We use a modified version of the star formation routine of Cen & Ostriker (1992). Star particles, representing the combined presence of a few million solar masses of stars, are formed when the following three conditions are met: (1) the total density of a grid cell is above a certain threshold, (2) a convergent flow exists (negative velocity divergence), and (3) the cooling time is less than the dynamical time. If all three conditions are satisfied, a "star particle," representing a large collection of stars, is formed within the grid cell with a total mass $m_* = f_* m_{\text{cell}} (\Delta t / t_{\text{dyn}})$. Here, $f_* \approx 0.1$ is the star formation efficiency, m_{cell} is the baryon mass in the cell, t_{dyn} is the dynamical time, and Δt is the hydrodynamical time step. Subsequently, this much mass is also removed from the grid cell as the star particle is formed, ensuring mass conservation. Although the star particle is formed instantaneously within the simulation, feedback occurs over a longer timescale, which more accurately reflects the gradual process of star formation.

The rate of star formation, and hence the rate at which thermal energy and metals are injected into the grid by the star particle, peaks after one dynamical time and then decays exponentially. Stellar feedback is represented by the injection of thermal energy and the return of gas and metals to the grid, in amounts proportional to $\Delta m_{\rm sf}$. A fraction (25%) of the stellar mass is returned to the grid as gas. The thermal energy and metals returned to the grid are $e = \epsilon (\Delta m_{\rm sf})c^2$ and $m_{\rm metals} = (\Delta m_{\rm sf})y$, where $\epsilon \approx 10^{-5}$ is the ratio of rest-mass energy to thermal energy and $y \approx 0.025$ is the metal yield. The distributed feedback method (Smith et al. 2011) distributed over a 27cell cube was designed to mitigate the overcooling that occurs when feedback is deposited into a single grid cell. This raises the temperature, gas density, and cooling rate to unphysically high values. Overcooling also causes the winds that should be transporting metals into the IGM to fizzle out and remain confined to their sites of origin. Smith et al. (2011) showed that this model is able simultaneously to provide good matches to the global star formation history and the observed number density per unit redshift of O VI absorbers (Danforth & Shull 2008). The local feedback method was significantly less successful.

To follow the cosmic star formation rate (SFR) history and the resulting injection of feedback, we have chosen to use Enzo 1024³ unigrid hydrodynamics without mesh refinement. We believe these "unigrid" calculations offer the most efficient use of scarce computational resources. With a box size of $50 h^{-1}$ Mpc, we have a comoving spatial resolution of $49 h^{-1}$ kpc, sufficient to resolve cosmic-web filaments and gravitational shocks throughout the IGM. This resolution may create some issues for resolving small galaxies at high redshift, which could affect the results for metallicity production and transport compared to AMR. However, our previous experiments (Smith et al. 2011) showed that AMR does not necessarily provide a better computation of the *global* SFR. In our simulations, star formation seems to be dependent on the force resolution on the root grid. Stars do not form in the lower-resolution simulations because the halos do not collapse correctly at early times when there is no refinement occurring in the box. By the time refinement happens, it is already too late; the collapse of the halos has already been delayed, owing to the poor force resolution. We have verified this by running simulations, with and without AMR, at the same resolution on the top grid. We find almost the exact same star formation history. For this reason, we decided to use constant high resolution everywhere and put our computational resources into a large unigrid: 1024³ in this paper, moving to 1536³ in recent work (Shull et al. 2012a) following the reionization epoch at $z \approx 6$ –20. By keeping a fixed (comoving) unigrid, we have less spatial resolution close to galaxy halos. In future studies, we intend to explore the effects of adding AMR around star-forming halos.

Post-processing of the simulations was carried out using the data analysis and visualization package yt^2 , documented by Turk et al. (2011). Our Enzo unigrid simulations (Smith et al. 2011), post-processed in the current paper, are among the best current work in describing the temperature, metallicity, and ionization state of the hot gas (WHIM) and photoionized gas. Our results have been checked for convergence and they are robust. These tests are discussed extensively in Smith et al. (2011) using several runs with different box sizes, resolutions, and modes of feedback (local and distributed), finding consistent results. In the current project, we seek to understand the thermal and ionization state of the IGM, including the distribution and covariance of metallicity, temperature, and O vi ionization fraction. In our simulations, the physical properties of Ovi absorbers and the degree to which they trace the WHIM are in good agreement with other recent simulations (Tepper-García et al. 2011; Cen & Chisari 2011). However, they differ significantly from those of Oppenheimer & Davé (2009) and Oppenheimer et al. (2012), who found that O vI and Ne vIII originate almost exclusively in warm ($T \approx 10^4$ K) photoionized gas. The SPH models by Oppenheimer & Davé (2009) and Davé et al. (2011) find IGM phases with markedly different temperatures and metallicities, but these results likely arise from their metal-injection schemes and the lack of mixing. Tepper-García et al. (2011) suggested that much of this difference arises because Oppenheimer & Davé (2009) neglected the effect of photoionization on metal-line cooling. Oppenheimer et al. (2012) investigated this claim by running additional simulations in which photoionization reduced the metal cooling. This reduction resulted in a small, but insufficient number of O VI absorbers associated with WHIM gas. Instead, they point to the fact that they do not include the mixing of metals from their galactic-wind particles, allowing feedback to take the form of cold, heavily enriched clouds.

Differences between AMR and SPH cosmological simulations have been analyzed in several studies. O'Shea et al. (2005b) compared the SPH code GADGET with the Eulerian grid code Enzo. Cosmological simulations run with dark matter only agree quite well, provided that Enzo is run with a sufficiently fine root grid; otherwise, low-mass halos are suppressed. For adiabatic gas dynamics, these authors found discrepancies in distributions of temperature, mass, and entropy in regions of low overdensity. In their comparison of simulations, these developers of both SPH and grid codes argued that "these discrepancies are due to differences in the shock-capturing abilities of the different methods." Similar concerns were expressed by Vazza et al. (2007), who noted the different phase diagrams of shocked cells in grid codes compared to SPH.

In examining the various interpretations of the high ions (O VI and Ne VIII), we have identified several key differences between the two codes: the Oppenheimer-Davé SPH code and our grid-based approach with Enzo. Other simulations (Cen & Ostriker 2006; Cen & Chisari 2011; Tepper-García et al. 2011; Smith et al. 2011; Cen 2012) find different results on IGM temperature and ionization state. Our current 1024³ simulations have better hydrodynamic resolution throughout the IGM than those of Tepper-García et al. (512³) and Davé & Oppenheimer (384^3) , but the schemes for feedback and mixing of metals differ. On the other hand, we have not employed the AMR capabilities of Enzo, which gives us less resolution around the galaxy halos. The disagreements between IGM temperatures and ionization mechanisms appear to arise from four effects: (1) different methods of injecting energy and metals (mixed or unmixed); (2) overcooling of unmixed, metal-enriched gas at high density and high metallicity; (3) differences in shock capturing (and shock-heating) between SPH and grid codes; and (4) differences in photoionization rates through the assumed radiation fields at $h\nu = 100-250$ eV. All four possibilities merit careful comparative studies, although we believe the resolution of this O vI controversy may ultimately hinge on understanding the nature of galactic winds and their ability to mix heavy elements into the IGM. Additional work is therefore needed to understand the hydrodynamic and resolution differences in the treatment of shocks and interfaces between hot and cold gas. Our future studies will attempt to distinguish between effects of hydrodynamics (code resolution) and feedback (injection of mass, energy, and metals).

3. CENSUS OF BARYONS IN DIFFERENT THERMAL PHASES

In this section, we provide a brief overview of the current observations of the baryon census at low redshift. We then present improvements in measuring the baryons in the two major components of the IGM: the WHIM as probed by O vI absorbers (Section 3.1) and the diffuse Ly α absorbers probed by H I (Section 3.2). Our improvements include both analytic models and numerical simulations, which allow us to understand the spatial variations of temperature, density, and metallicity throughout the IGM.

Observations of the 'Ly α forest' of absorption lines suggest that it contains $\sim 30\%$ of the low-z baryons (Penton et al. 2000, 2004; Lehner et al. 2007; Danforth & Shull 2008). Another 30%–40% is predicted by simulations to reside in shock-heated gas at 10⁵ K to 10⁷ K (WHIM). These two components account for 60%–70% of the cosmological baryons. However, owing to its low density, the WHIM is difficult to detect in emission (Soltan 2006). More promising are absorption-line studies that use the high ionization states of abundant heavy elements with resonance lines in the far-ultraviolet (CIV, NV, OVI), extreme ultraviolet (OIV, OV, NeVIII), and soft X-ray (OVII, OVIII, N vI, Ne IX). Gas in the temperature range $5 < \log T < 6$ can also be detected in broad Ly α absorption (Richter et al. 2004; Danforth et al. 2010) arising from trace amounts of neutral hydrogen with neutral fractions $-6.6 < \log f_{\rm HI} < -4.8$. By far, the most effective surveys of the low-z WHIM were obtained from the O vI lines at 1031.926 Å and 1037.617 Å (Danforth & Shull 2005, 2008; Tripp et al. 2008; Thom & Chen 2008), which probe the temperature range $10^{5.3-5.7}$ K in collisionally ionized gas. Danforth & Shull (2008) measured the column

² http://yt.enzotools.org/



Figure 1. Distribution of IGM in temperature T and baryon overdensity $\Delta_b = \rho_b/\overline{\rho}_b$, color-coded by baryon mass fraction. This distribution shows the same thermal phases seen in simulations by other groups, commonly labeled as warm (diffuse photoionized gas), WHIM, and condensed.

densities of 83 O VI absorbers and estimated that $8.6\% \pm 0.8\%$ of the baryons reside in this phase, assuming constant correction factors for the metallicity ($Z \approx 0.1 Z_{\odot}$) and O VI ionization fraction ($f_{\rm O VI} = 0.2$). A few detections of Ne VIII have also been reported (Savage et al. 2005, 2011; Narayanan et al. 2009, 2011; Meiring et al. 2012) probing somewhat hotter gas (log $T \approx 5.7 \pm 0.2$).

To detect even hotter portions of the WHIM at $\log T > 6$ probably requires searches for trace metal absorption lines from highly ionized C, O, or Ne. These weak X-ray absorption lines are difficult to detect with the current throughput and spectral resolution of spectrographs on Chandra and XMM-Newton (Yao et al. 2012). Possible X-ray detections of hotter gas at $(1-3) \times 10^6$ K have been claimed, using absorption lines of helium-like O VII λ21.602 (Nicastro et al. 2005a, 2005b, 2008; Buote et al. 2009; Fang et al. 2010; Zappacosta et al. 2010) and hydrogenic O VIII λ 18.969 (Fang et al. 2002, 2007). Most of these Chandra detections remain controversial and unconfirmed by the XMM-Newton satellite (Kaastra et al. 2006; Williams et al. 2006; Rasmussen et al. 2007). For example, recent analyses of spectroscopic data on Mrk 421 fail to detect any WHIM gas at the claimed redshifts (z = 0.01 and 0.027), either in broad Ly α absorption (Danforth et al. 2011) from high signal-to-noise (S/N) data from the cosmic origins spectrograph (COS) on the HST or in O VII (Yao et al. 2012) in Chandra data.

The post-processed results of our simulations relevant to O vI and H I are illustrated in Figures 1–8. Figure 1 shows the distribution of baryons in the two-dimensional phase space of baryon temperature and overdensity (log T, log Δ_b) color-coded by baryon mass fraction. Figure 2 shows the neutral fraction, $f_{\rm HI}$, also plotted versus log T and log Δ_b . The commonly found features in these phase-space plots include the diffuse Ly α

absorbers ($T = 10^{3.0-4.5}$ K and $\Delta_b = 10^{-2}$ to $10^{+1.5}$), a condensed phase ($\Delta_b > 10^3$), and a shocked-heated plume of WHIM ($T = 10^{5-7}$ K and $\Delta_b = 10^0-10^{2.5}$). Most of the narrow Ly α absorbers are believed to be photoionized, although broad Ly α absorbers (BLAs) may arise in the collisionally ionized WHIM, becoming detectable when log $f_{\rm H1} > -6.5$. The gas traced by O vI and BLAs resides at temperatures $5 < \log T < 6$, marked in Figure 3 for the cumulative distribution of mass and metals versus temperature. The two curves show results from our simulations with distributed feedback (energy injected into 27 cells) and local feedback (single cell). Figure 4 shows the cumulative mass distribution of O vI versus column density and indicates that a significant fraction of O vI is traced by weak absorbers with log $N_{\rm O vI} \leq 13.5$ (equivalent width $W_{\lambda} < 40$ mÅ for the stronger 1032 Å line).

Our simulations track many O vI properties, including metallicity, temperature, and ionization fraction. Figures 5 and 6 show the range and covariance of the two correction factors used in the baryon census: metallicity in solar units (Z/Z_{\odot}) and O vI ionization fraction $f_{O vI}$. The ionization fraction includes the effects of both collisional ionization and photoionization, as discussed by Smith et al. (2011). Figure 5 color-codes these distributions in column density, $N_{O_{VI}}$, while Figure 6 illustrates their distribution in temperature and baryon overdensity. In multiphase gas, several mechanisms can produce O vi (113.87 eV is needed to ionize Ov) including collisional ionization at $\log T > 5$ and photoionization by the (EUV) metagalactic background. The dashed line in Figure 6 shows the locus of points (log T and log Δ_b) at which collisional ionization equals photoionization. This calculation is based on Ov collisional ionization rates from Shull & Van Steenberg (1982). The O v photoionization rate was derived assuming a cross section $\sigma(E) = (0.36 \times 10^{-18} \text{ cm}^2)(E/113.87 \text{ eV})^{-2.1}$ and the



Figure 2. Distribution of hydrogen neutral fraction, f_{H1} , in temperature *T* and baryon overdensity $\Delta_b = \rho_b/\overline{\rho}_b$. The color scale to the right shows log f_{H1} . This distribution shows thermal phases labeled as warm (diffuse photoionized), WHIM, and condensed gas. (A color version of this figure is available in the online journal.)

EUV radiation field at 8–10 ryd from Figure 13 of Haardt & Madau (2012).

Figure 7 shows the distribution of the product, $(Z/Z_{\odot})f_{\rm OVI}$, throughout the simulation grid. Color-coded by OVI mass fraction, this product exhibits a bimodal distribution with temperature and baryon overdensity. In the deepest-red portions representing high OVI mass fraction, one finds regions with large values, $(Z/Z_{\odot})f_{\rm OVI} \approx 10^{-1.3}$, in high-density filaments with $\Delta_b \approx 100$, and regions with lower values, $(Z/Z_{\odot})f_{\rm OVI} \approx 10^{-2.5}$ at $\Delta_b \approx 10$. In converting the column densities of OVI absorbers to baryons, one should not adopt single corrections for metallicity and ionization fraction. Instead, as described in Section 3.1, we apply statistical corrections based on the correlation of the product $(Z/Z_{\odot})f_{\rm OVI}$ with OVI column density (Figure 8).

3.1. Warm-hot IGM Probed in O vi Absorption

We can use the simulations to derive the distribution of metallicity and O vI ionization fraction throughout the multiphase IGM. Both quantities vary throughout the grid in the simulated IGM. Moreover, the product $(Z/Z_{\odot}) f_{OvI}$ correlates with N_{OvI} (Figure 8) with weaker absorbers having systematically lower values. This is primarily an effect of spatial variations in the metallicity, but also variations in the O vI ionization fraction produced by spatial fluctuations in WHIM temperature and contributions from photoionizing radiation on low-density IGM. The baryon content in O vI-traced WHIM is then given by an integral over O vI column density (*N*), with the corrections for metallicity and ionization fraction placed inside the integral:

$$\Omega_{b}^{(\text{O VI})} = \left[\frac{\mu_{b}H_{0}}{c\rho_{\text{cr}}(\text{O}/\text{H})_{\odot}}\right] \int_{N_{\text{min}}}^{N_{\text{max}}} \frac{d\mathcal{N}(N)}{dz} \frac{N}{Z_{\text{O}}(N) f_{\text{O VI}}(N)} dN.$$
(1)

Here, $\mu_b = 1.33 m_{\rm H}$ is the mean baryon mass per hydrogen nucleus, accounting for helium. Earlier surveys that used O vI as a baryon tracer assumed constant values of the ionization fraction, $f_{\rm O vI} = 0.2$ (its maximum value in collisional ionization equilibrium at log $T_{\rm max} = 5.45$), and metallicity, $Z/Z_{\odot} = 0.1$, relative to the solar oxygen abundance, $(O/H)_{\odot} = 4.90 \times 10^{-4}$ (Asplund et al. 2009).

From our simulations (Figure 8), the product of metallicity and O vI ionization fraction has a statistical power-law dependence on O vI column density, scaling as N^{γ} ,

$$(Z/Z_{\odot})f_{\rm O\,vI} = (0.015)(N_{\rm O\,vI}/10^{14}\,{\rm cm}^{-2})^{0.70}$$
. (2)

Integrating over the observed distribution $dN/dz \propto N^{-\beta}$, we find

$$\Omega_b^{(\rm O\, v_I)} \propto \int_{N_{\rm min}}^{N_{\rm max}} N^{1-\gamma-\beta} \, dN \propto \left[N_{\rm min}^{2-\gamma-\beta} - N_{\rm max}^{2-\gamma-\beta} \right]. \tag{3}$$

For $\gamma \approx 0.70$ and the observed $\beta \approx 2.0$ (Danforth & Shull 2008), the integral increases at the low end as $N_{\min}^{-0.7}$. The column-density-weighted mean of the product $f_{O_{VI}}(Z/Z_{\odot}) = 0.01$, a factor of two smaller than previously assumed. For our standard integration range, $13.0 \leq \log N_{O_{VI}} \leq 15.0$, this correction doubles the number of baryons in the O VI-traced WHIM, compared to previous assumptions. As noted earlier, we found similar results in all our simulations.

Previous O VI surveys and baryon estimates were quantified by an absorption-line frequency, $d\mathcal{N}/dz$, per unit redshift and an O VI-traced baryon fraction, $\Omega_b^{(O VI)}/\Omega_b$. Using 40 O VI absorbers seen with *FUSE*, Danforth & Shull (2005) found $d\mathcal{N}/dz \approx 17 \pm 3$ for column densities $13.0 \leq N_{\rm O VI} \leq 14.5$. The 10^{13} cm⁻² lower limit corresponds to 12.5 mÅ equivalent width in O VI $\lambda 1032$. The 2005 *FUSE* census gave an



Figure 3. Cumulative distributions of IGM mass (top panel) and metals (bottom panel) vs. temperature *T* from our simulations, run with both "local" and "distributed" feedback (Smith et al. 2011). We only show IGM baryons with overdensities $\Delta_b < 1000$; the remaining mass and metals are in galaxies and collapsed phase. Vertical dashed lines mark the temperature range (10^5-10^6 K) probed by O vI and Ne vIII, and horizontal lines show intercepts for the two distributions. (A color version of this figure is available in the online journal.)

O vI-traced baryon fraction of at least $4.8\% \pm 0.9\%$ (statistical error only) for a correction factor $f_{\rm O\,VI}(Z/Z_{\odot}) = 0.02$. Danforth & Shull (2008) used *HST*/STIS data on 83 O VI absorbers to find $d\mathcal{N}/dz \approx 15.0^{+2.7}_{-2.0}$ integrated down to 30 mÅ, with $d\mathcal{N}/dz \approx 40^{+14}_{-8}$ integrated to 10 mÅ. Their derived WHIM baryon fractions were $7.3\% \pm 0.8\%$ and $8.6\% \pm 0.8\%$, integrated to 30 mÅ and 10 mÅ, respectively. Tripp et al. (2008) found a similar line frequency, $d\mathcal{N}/dz \approx 15.6^{+2.0}_{-2.4}$, for 51 intervening O VI absorption systems integrated to 30 mÅ, while Thom & Chen (2008) found $d\mathcal{N}/dz \approx 10.4 \pm 2.2$ for 27 O VI absorbers down to 30 mÅ. The latter survey was more conservative, requiring detection of both the stronger O VI line at 1032 Å and the weaker line at 1038 Å. They also had fewer sight lines (16) and a smaller number of O vI absorbers (27) in their survey. Their line frequency is smaller than those in other O vI surveys, perhaps because of small-number statistics and the two-line detection requirement.

As part of a Hubble Archive Legacy Project (PI: Shull, HST-AR-11773.01-A), the Colorado group has re-analyzed *HST*/STIS data on IGM absorption lines (Tilton et al. 2012), finding 746 H_I absorbers and 111 O v_I absorbers. Through a critical evaluation of data in the literature and comparison to high-S/N COS spectra when available, we corrected line identification errors in Danforth & Shull (2008) and other surveys. The O v_I line frequency from Tilton et al. (2012) is $d\mathcal{N}/dz \approx 22.2^{+3.2}_{-2.4}$ integrated to 30 mÅ equivalent width



Figure 4. Cumulative distribution of O v1 by mass from our WHIM simulation, for column densities $N_{O v1} = 10^{12} - 10^{16} \text{ cm}^{-2}$. Solid black line shows cumulative mass fraction, labeled on left vertical axis. Gray histogram shows cumulative number of O v1 absorbers, labeled on right vertical axis. Red points show observed cumulative column-density distribution (Danforth & Shull 2008) labeled on right vertical scale. A significant fraction of O v1-traced WHIM resides in weak absorbers, although the distribution flattens at log $N_{O v1} < 13.5$.



Figure 5. Distribution of IGM metallicity (Z/Z_{\odot}) and O vI ionization fraction $(f_{O VI})$ color-coded by O vI column density. Note the wide range and covariance of individual factors, whose product, $f_{O VI}(Z/Z_{\odot})$, correlates with O vI column density (color bar along right). (A color version of this figure is available in the online journal.)

in O vI $\lambda 1032$, with a slope $\beta = 2.08 \pm 0.12$. Down to 10 mÅ, they find $dN/dz \approx 42.0^{+10.7}_{-6.3}$. This new survey provides more reliable baryon fractions for the O vI-traced WHIM of 7.2% $\pm 0.8\%$ (integrated down to 30 mÅ equivalent width) and 8.6% $\pm 0.7\%$ (to 10 mÅ), using the old correction factor, $f_{O vI}(Z/Z_{\odot}) = 0.02$. Taken as a whole, these O vI surveys

suggest a WHIM baryon fraction of 8%–9%, assuming the old values of metallicity and ionization fraction. With our new correction factors, $f_{O_{VI}}(Z/Z_{\odot}) = 0.01$, the baryon fractions double. We therefore adopt an O_{VI}-traced baryon fraction of 17% ± 4%, where we have increased the error to account for systematic uncertainties. There are also corrections for possible



Figure 6. Distribution of IGM temperature versus baryon overdensity, $\Delta_b = \rho_b/\overline{\rho}_b$, color-coded by O VI mass fraction. In this phase space, we identify the WHIM $(T \ge 10^5 \text{ K})$, warm, diffuse photoionized gas $(T < 10^5 \text{ K} \text{ and } \Delta_b < 1000)$, and condensed gas $(\Delta_b > 1000)$. Dashed line shows locus at which collisional ionization equals photoionization (collisional ionization dominates above the dashed curve). (A color version of this figure is available in the online journal.)



Figure 7. Distribution of the metallicity–ionization product, $(Z/Z_{\odot})f_{OVI}$, vs. baryon overdensity, $\Delta_b = \rho_b/\overline{\rho}_b$, color-coded by OVI mass fraction. The broad distribution of the product, from 0.001 to 0.1, has local enhancements (deep red) in low-metallicity regions (overdensities $\Delta_b \approx 10$) and high-metallicity regions ($\Delta_b \approx 100$). The column-density-weighted mean of this product is 0.01 (see Figure 8).



Figure 8. Values of the product $(Z/Z_{\odot})f_{O VI}$ for the WHIM simulation with distributed feedback overlaid with a power-law fit (solid red line) to the ensemble, $(0.015)[N_{O VI}/10^{14} \text{ cm}^{-2}]^{0.70}$. Results from simulations with local feedback are similar. Integrating over the observed distribution in $N_{O VI}$, we find a weighted value of 0.01. Horizontal (blue) line shows previously assumed value of 0.02 for this product $(Z/Z_{\odot} = 0.1 \text{ and } f_{O VI} = 0.2)$. Typical variance (1σ) about this fit is 0.3–0.4 dex, shown by red dashed lines.

double-counting: for example, strong BLAs with metals may contain detectable O vI, and some Ly α forest absorbers may contain photoionized O vI. These issues are discussed in Section 4.1.

The value of $\Omega_b^{(\text{Ovi})}$ is dominated by weak absorbers with $N_{\text{Ovi}} < 10^{13.5} \text{ cm}^{-2}$, where absorption-line statistics become uncertain. An accurate O vI census requires measuring even weaker O vI $\lambda 1032$ absorption lines with $N_{\text{Ovi}} < 10^{13} \text{ cm}^{-2}$ corresponding to equivalent widths $W_{\lambda} =$ $(12.5 \text{ mÅ})(N_{\text{Ovi}}/10^{13} \text{ cm}^{-2})$. Deep spectroscopic surveys in O vI can also ascertain where the distribution of O vI absorbers flattens (Figure 4).

3.2. Diffuse Lya Absorbers

In this section, we describe the ionization corrections needed to translate H I (Ly α) absorption surveys into baryon content. As with O VI, we use simulations to derive the distribution of hydrogen neutral fraction, $f_{\rm H I}$, throughout the multiphase IGM. We then compare our numerical results to those from analytic calculations. The numerical simulation results are based on the distribution of $f_{\rm H I}$ over the grid of phase-space parameters (log *T*, log Δ_b) in our 1024³ simulations with 50 h^{-1} Mpc boxes. Summing the baryon masses over this grid, subject to various cuts in $f_{\rm H I}$, *T*, and Δ_b , we derive baryon fractions corresponding to the Ly α forest, BLAs (WHIM), hot gas, and condensed gas.

Table 1 shows the parameter cuts and results of this exercise for models with both local and distributed feedback (Smith et al. 2011). The rows are arranged to cover a three-decade range in neutral fraction, from $-7 < \log f_{\rm H_{I}} < -4$, plus gas outside

that range (hot gas at $\log T > 6.3$ and condensed gas with $\log f_{\rm H1} > -4$). For both feedback schemes, photoionized Ly α forest absorbers generally have neutral fractions in the range $-6 < \log f_{\rm H1} < -4$, with temperatures classified as "warm" ($3 < \log T < 5$). These diffuse Ly α absorbers comprise 32.3% and 34.4% of the baryons for the distributed and local feedback schemes, respectively. Both runs have \sim 82% of the gas with $\log f_{\rm H1} < -7$ (undetectable in Ly α absorption) residing in the WHIM, with the remainder in hot (\sim 10%) and condensed (\sim 8%) phases. Gas with $-7 < \log f_{\rm H1} < -6$ should be detectable as BLAs. In the simulations, these absorbers have a 2:1 ratio of WHIM to warm phase, with almost none in the other phases. Gas with $-5 < \log f_{\rm H1} < -4$ is almost entirely in the warm phase (\sim 97%).

These numerical estimates that $\sim 33\%$ of the baryons are traced by the Ly α agree well with our analytic calculations. To better elucidate this comparison, we describe the formalism (Penton et al. 2000) in more detail, including assumptions for the photoionization corrections to the HI (Ly α) absorbers. In photoionization equilibrium, the density of neutral hydrogen in low-density gas depends on the ionizing background, gas density, and electron temperature, all of which evolve with redshift and have spatial fluctuations,

$$n_{\rm H_{I}} = \frac{n_e \, n_{\rm H} \, \alpha_{\rm H}^{(A)}(T)}{\Gamma_{\rm H}} \,.$$
 (4)

Here, $n_e = (1 + 2y) = 1.165n_{\rm H}$ is the electron density for fully ionized gas, $n_{\rm H}$ is the total density of hydrogen nuclei, and $y = n_{\rm He}/n_{\rm H} = [(Y/4)/(1 - Y)] \approx 0.0823$ is the



Figure 9. Compilation of the mean AGN spectral energy distribution (SED), pinned at 1 ryd, with $I_0 = 2 \times 10^{-23}$ erg cm⁻² s⁻¹ Hz⁻¹ sr⁻¹ and two different flux distributions, $F_{\nu} \propto \nu^{-\alpha_s}$. Previous composite spectra from small numbers of AGNs are shown in red (*HST*) and light blue (*FUSE*), with slopes $\alpha_s = 1.76 \pm 0.12$ (Telfer et al. 2002) and $\alpha_s = 0.56^{+0.38}_{-0.28}$ (Scott et al. 2004). Soft X-ray data are from *ROSAT* observations of AGNs in the Lockman hole (Hasinger 1994) normalized at E = 1 keV (73.53 ryd) with spectral slope $F_E \propto E^{-0.96 \pm 0.11}$. The ionization potentials of H I and He II and ionization energies to produce key metal ions are shown as arrows. The metagalactic backgrounds are from Haardt & Madau (2001, 2012).

 Table 1

 Baryon Content Probed by f_{HI} in Simulations

Primary Thermal Phases	Range in $f_{\rm HI}$	Baryon Content ^a (Distributed Feedback)	Baryon Content ^a (Local Feedback)
WHIM $(\log T > 6.3)$	$-10 < \log f_{\rm H_{I}} < -7$	28.3% of baryons	25.2% of baryons
WHIM $(5 < \log T < 6.3) + Warm$	$-7 < \log f_{\rm HI} < -6$	29.4% of baryons	27.8% of baryons
Warm photoionized Ly α forest	$-6 < \log f_{\rm HI} < -5$	25.8% of baryons	27.4% of baryons
Warm photoionized Ly α forest	$-5 < \log f_{\rm HI} < -4$	6.5% of baryons	7.0% of baryons
Condensed phase (log $\Delta_h > 3$)	$-4 < \log f_{\rm HI} < 0$	10.0% of baryons	12.6% of baryons
Total baryons	200	100%	100%

Note.

^a Cuts on grid (Figure 2) are in neutral fraction $(f_{\rm H1})$, baryon overdensity (Δ_b) , and temperature (T) as shown in first column. Warm phase refers to photoionized gas at $3 < \log T < 5$. WHIM refers to gas at $5 < \log T < 7$, where Ly α absorbers with $5 < \log T < 6$ are detectable as broad Ly α absorbers $(b > 40 \text{ km s}^{-1})$ with log $f_{\rm H1} > -6.5$). Last two columns give fraction of baryons in each phase, as traced by $f_{\rm H1}$. We use the 1024^3 simulations in $50 h^{-1}$ Mpc boxes, with both local and distributed feedback.

helium-to-hydrogen ratio by number, assuming Y = 0.2477helium abundance by mass. For the low values of $n_{\rm H}$ and $N_{\rm H_{I}}$ in IGM absorbers, we adopt the hydrogen case-A radiative recombination rate coefficient, $\alpha_{\rm H}^{(A)}(T) \approx (2.51 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1})T_{4.3}^{-0.726}$, scaled to an electron temperature $T = (10^{4.3} \text{ K}) T_{4.3}$ characteristic of low-metallicity IGM (Donahue & Shull 1991). The H I photoionization rate depends on the metagalactic radiation field, with specific intensity $I_{\nu} = I_0(\nu/\nu_0)^{-\alpha_s}$ referenced to the Lyman limit, $h\nu_0 = 13.6 \text{ eV}$. Here, $\langle \alpha_s \rangle \approx 1.6-1.8$ is the mean QSO spectral index between 1.0–1.5 ryd (Telfer et al. 2002; Shull et al. 2012b). The frequency-integrated photoionization rate is given by the approximate formula, $\Gamma_{\rm H} \approx [4\pi I_0 \sigma_0 / h(\alpha_s + 3)] \approx (2.49 \times 10^{-14} \text{ s}^{-1}) I_{-23}(4.8/\alpha_s + 3)$, where $I_0 = (10^{-23} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1}) I_{-23}$. Hereafter, we combine the two parameters, I_0 and α_s , into a single scaling parameter, $\Gamma_{-14} = (\Gamma_{\rm H}/10^{-14} \text{ s}^{-1})$, for the hydrogen photoionization rate. Previous calculations of the low-*z* ionizing intensity (Shull et al. 1999) found $\Gamma_{\rm H} \approx 3.2^{+2.0}_{-1.2} \times 10^{-14} \, {\rm s}^{-1}$ and noted that low-*z* observational constraints were consistent with values in this range. More recent calculations (Haardt & Madau 2012) are consistent with this value and other estimates at $z \approx 0$. Figure 9 illustrates current estimates of the intensity of the metagalactic ionizing radiation field starting at 1 ryd (H I photoionization edge), continuing to 4 ryd (He II edge) and beyond, including ionization potentials needed to produce some of the higher metal ions, such as C IV (47.87 eV = 3.52 ryd), O VI (113.87 eV = 8.37 ryd), O VII (138.08 eV = 10.15 ryd), Ne VIII (207.2 eV = 15.24 ryd), and O VIII (739.11 eV = 54.35 ryd).

The Ly α absorbers are thought to arise as fluctuations in dark matter confined clumps or filaments, which we approximate as singular isothermal spheres with density profiles, $n_{\rm H}(r) = n_0(r/r_0)^{-2}$ normalized to a fiducial radius r_0 . For a sight line passing through an absorber at impact parameter p, the total baryon mass within radius r = p is $M_b(p) = 4\pi\mu_b n_0 r_0^2 p$, where $\mu_b = (1 + 4y)m_{\rm H} \approx 1.33m_{\rm H}$ is the mean baryon mass per hydrogen. The H_I column density can be derived, using the density-squared dependence of $n_{\rm H_I}$ and integrating through the cloud along path length ℓ at impact parameter p, where $\ell^2 = r^2 - p^2$. We substitute $p = r \cos \phi$ and $\ell = p \tan \phi$ for the angle ϕ between the directions of p and r,

$$N_{\rm H\,I}(p) = \left[\frac{\alpha_{\rm H}^{(\rm A)} \left(1+2y\right)}{\Gamma_{\rm H}}\right] 2 \int_0^\infty n_0^2 \left(\frac{r}{r_0}\right)^{-4} dl$$
$$= \left[\frac{\pi n_0^2 r_0^4 \,\alpha_{\rm H}^{(\rm A)} \left(1+2y\right)}{2 \,\Gamma_{\rm H} \, p^3}\right].$$
(5)

Solving for the quantity $n_0 r_0^2$, we can express the absorber mass within r = p as

$$M_b(p) = 4\pi \mu_b \ p^{5/2} \left[\frac{2 \Gamma_{\rm H} N_{\rm HI}(p)}{\pi (1+2y) \alpha_{\rm H}^{(A)}} \right]^{1/2}$$

= $(1.09 \times 10^9 \ M_{\odot}) \left[N_{14}^{1/2} \ \Gamma_{-14}^{1/2} \ p_{100}^{5/2} T_{4.3}^{0.363} \right] .$ (6)

In the above formula, we have scaled the impact parameter $p = (100 \text{ kpc}) p_{100}$ using a 100 kpc characteristic scale length of Ly α absorbers at fiducial column density $N_{\text{H}\text{I}} = (10^{14} \text{ cm}^{-2})N_{14}$; see Penton et al. (2000), and references therein.

Next, we calculate the baryon density in the Ly α absorbers as a fraction of the cosmological closure density, $\rho_{cr} = (3H_0^2/8\pi G)$ at z = 0. Because our Ly α survey extends to z = 0.4, we include corrections for cosmological evolution in the space density of absorbers, $\phi(z)$, and the hydrogen photoionization rate, $\Gamma_{\rm H}(z)$. We begin with the standard expression for the number of absorbers per unit redshift,

$$\frac{d\mathcal{N}}{dz} = \left[\frac{c}{(1+z)H(z)}\right]\pi[p(z)]^2\phi(z), \qquad (7)$$

where $H(z) = H_0 [\Omega_m (1+z)^3 + \Omega_\Lambda]^{1/2}$ is the Hubble parameter at redshift z in a flat Λ CDM cosmology, and the absorber space density is $\phi(z) = \phi_0 (1+z)^3$. The absorption-line frequency and impact parameter p correspond to the H_I column density and absorber mass given in Equations (5) and (6). The baryon mass density in Ly α absorbers at redshift z is written as the product of absorber mass, M_b , times the absorber space density, $\phi(z)$, integrated over the distribution in H_I column density. We define the closure parameter, $\Omega_b^{(H_I)} = \rho_b(0)/\rho_{cr}(0)$ at z = 0, where $\rho_b(z) = \rho_b(0)(1+z)^3$. Assembling all the terms, we find a closure parameter in Ly α absorbers of column density N_{H_I} ,

$$\Omega_{b}^{(\text{H}_{I})} = \frac{\phi_{0}M_{b}}{\rho_{\text{cr}}} = \frac{32(2\pi)^{1/2}}{3} \left[\frac{\mu_{b}G}{cH(z)(1+z)^{2}} \right] \\ \times \left[\frac{\Gamma_{\text{H}}(z)p(z)N_{\text{H}_{I}}}{(1+2y)\alpha_{\text{H}}^{(\text{A})}} \right]^{1/2}.$$
(8)

Recent calculations of the metagalactic ionizing background (Haardt & Madau 2012) show that the hydrogen photoionization rate rises rapidly from redshifts z = 0 to z = 0.7. We have fitted the rate to the convenient formula $\Gamma_{\rm H}(z) = (2.28 \times 10^{-14} \text{ s}^{-1}) (1 + z)^{4.4}$. We have little data on the redshift evolution of the characteristic absorber scale length, p, other than theoretical

expectations for the gravitational instability of filaments in the cosmic web. In the following calculation, we assume that $p = (100 \text{ kpc})p_{100}$ remains constant with redshift and rewrite Equation (8) as an integral over column density,

$$\Omega_{b}^{(\mathrm{H}_{1})} = (9.0 \times 10^{-5}) \frac{h_{70}^{-1} p_{100}^{1/2} T_{4.3}^{0.363} (1+z)^{0.2}}{[\Omega_{m} (1+z)^{3} + \Omega_{\Lambda}]^{1/2}} \\ \times \int_{N_{\min}}^{N_{\max}} \frac{d\mathcal{N}(\log N_{\mathrm{H}_{1}})}{dz} N_{14}^{1/2} d(\log N_{\mathrm{H}_{1}}) .$$
(9)

The ionization rate, $\Gamma_{\rm H}(z) \propto (1+z)^{4.4}$, enters Equation (8) as the square root, almost exactly compensating for the $(1+z)^2$ factor in the denominator.

We can now use $Ly\alpha$ surveys to evaluate their contribution to the baryon census from our analytic formalism. Ultraviolet spectrographic surveys of low-redshift absorbers provide the distribution of H_I column densities in the diffuse Ly α forest (Penton et al. 2000, 2004; Danforth & Shull 2008; Lehner et al. 2007; Tilton et al. 2012). Penton et al. (2004) applied photoionization corrections to a survey of 187 Ly α absorbers over redshift path length $\Delta z = 1.157$ and found a distribution in H I column density, $f(N) \propto N^{-\beta}$ with $\beta = 1.65 \pm 0.07$ and a $29\% \pm 4\%$ contribution to the total baryon content. Danforth & Shull (2008) surveyed 650 Ly α absorbers with HST/STIS over the range $12.5 \leq \log N_{\rm H_{I}} \leq 16.5$ with total path length $\Delta z =$ 5.27. Their H I distribution was similar, with $\beta = 1.73 \pm 0.04$ and a fractional contribution of $28.7\% \pm 3.7\%$ (statistical errors only) to the baryon census. Although the formulas for baryon fractions were stated correctly (Equations (7)-(10) in Danforth & Shull 2008), the values listed in their Tables 12 and 13 were computed with incorrect cosmological corrections and overestimated values of Ω_b for HI and OVI. Our new HST archive survey (Tilton et al. 2012) properly includes these effects, as well as the redshift evolution of $\Gamma_{\rm H}(z)$, to find $\beta = 1.68 \pm 0.03$ for 746 Ly α systems with column densities between $12.5 < \log N_{\rm H\,I} < 16.5$ over path length $\Delta z = 5.38$.

The new derivation (Tilton et al. 2012) of $\Omega_b^{(\text{H1})}$ is consistent with 24%–30% of the baryons residing in the Ly α forest and partial Lyman-limit systems. This value, derived using the analytic formalism above, agrees fairly well with estimates of 32%–34% from our numerical simulations (Table 1). For the current census, we adopt an Ly α forest baryon fraction of $\Omega_b^{(\text{H1})} = 28\% \pm 11\%$. The latter error bars include systematic effects, as we discuss in Section 4.

4. STATUS OF BARYON CENSUS

We now summarize the current status of the low-z baryon census and describe the individual baryon contributions, together with previous estimates and uncertainties. Figure 10 shows a pie chart of the current observable distribution of low-redshift baryons in various forms, from collapsed structures to various phases of the IGM, CGM, and WHIM. These slices show the contributions, $\Omega_b^{(i)}/\Omega_b^{(tot)}$, to the total baryon content from components (*i*). Measurements of Ly α , O vI, and BLAs, together with more careful corrections for metallicity and ionization fraction, can now account for ~60% of the baryons in the IGM. An additional 5% may reside in circumgalactic gas, 7% in galaxies, and 4% in clusters. This still leaves a substantial fraction, 29% ± 13%, unaccounted for. We have assigned realistic errors on each of the "slices of the baryon pie," most of which involve systematic uncertainties in the parameters needed for the THE ASTROPHYSICAL JOURNAL, 759:23 (15pp), 2012 November 1



Figure 10. Compilation of current observational measurements of the lowredshift baryon census (Section 3.3). Slices of the pie chart show baryons in collapsed form, in the circumgalactic medium (CGM) and intercluster medium (ICM), and in cold gas (H 1 and He 1). Primary baryon reservoirs include diffuse photoionized Ly α forest and WHIM traced by O v1 and broad Ly α absorbers. Blended colors (BLAs and O v1) have a combined total of 25% ± 8%, smaller than their direct sum (17% plus 14%) owing to corrections for double-counting of WHIM at 10⁵–10⁶ K with detectable metal ions (Section 4.1). Collapsed phases (galaxies, CGM, ICM, cold neutral gas) total 18% ± 4%. Formally, 29% ± 13% of the baryons remain unaccounted for. Our simulations (Figure 3) suggest that an additional 15% reside in X-ray-absorbing gas at $T \ge 10^{6.3}$ K. Additional baryons may be found in weaker lines of low-column-density O v1 and Ly α absorbers. Deeper spectroscopic UV and X-ray surveys are desirable. (A color version of this figure is available in the online journal.)

ionization corrections, metallicity, and geometric factors (cloud size). It is possible that the baryon inventory could change as a result of better determinations of these parameters. However, most numerical simulations including ours (Figure 3) suggest that a substantial reservoir (~15%) of hot baryons exists in the hotter WHIM ($T > 10^6$ K).

4.1. Components of Baryon Content

The following paragraphs summarize our current knowledge of the baryon content in various components and thermal phases of the IGM.

1. Photoionized Lya absorbers. For this paper, we adopt $\Omega_{h}^{(\text{H}_{I})} = 28\% \pm 11\%$ based on the results of Danforth & Shull (2008), our new survey (Tilton et al. 2012), and the systematic uncertainties discussed in Section 3.2. The midrange distribution in column densities, $13.0 < \log N_{\rm HI} <$ 14.5, is fairly well characterized, but the numbers of high-column absorbers are small. Their contribution to Ω_b remains uncertain owing to corrections for their size and neutral fraction. At the low end of the columndensity distribution, there could be modest contributions to the baryon content from weaker $Ly\alpha$ absorbers. In current surveys, their numbers are increasingly uncertain at $\log N_{\rm HI}$ < 13 (our integration was down to 12.5). For a power-law distribution with $\beta = 1.7$, extending the distribution from $\log N = 12.5$ down to 12.0 would increase the baryon fraction by another 10% (from 28% to 31%). For this paper (Figure 10), we adopt $\Omega_b^{(\text{H}_1)} = 28\% \pm 11\%$ based on the results of Danforth & Shull

(2008), Tilton et al. (2012), and the systematic uncertainties discussed in Section 3.2.

- 2. WHIM (O vI-traced). Previous FUSE surveys of intergalactic O vI absorbers (Danforth & Shull 2005; Tripp et al. 2006) found lower limits of 5% and 7%, respectively for the contribution of this gas to the baryon inventory. These surveys assumed metallicity $Z = 0.1 Z_{\odot}$ and ionization fraction $f_{O vI} = 0.2$. In 2008, three O vI surveys with HST/STIS (Danforth & Shull 2008; Tripp et al. 2008; Thom & Chen 2008) probed to lower O vI column densities. Based on the survey of 83 O vI absorbers (Danforth & Shull 2008) and our more recent analysis of 111 O vI absorbers (Tilton et al. 2012), we adopt a baryon fraction $\Omega_b^{(O vI)} = 17\% \pm 4\%$. The factor-of-two increase arises primarily from our revised corrections, $(Z/Z_{\odot}) f_{O vI} = 0.01$, for metallicity and O vI ionization fraction (see Section 3.1). There may be some, as yet undetermined, overlap of photoionized O vI with the Ly α forest.
- 3. WHIM (BLA-traced). BLAs were proposed (Richter et al. 2004, 2006; Lehner et al. 2006, 2007) as repositories of a substantial fraction of the low-redshift baryons. BLAs are defined as $Ly\alpha$ absorbers with Doppler parameters $b \ge 40 \text{ km s}^{-1}$, corresponding to temperatures $T = (m_{\rm H}b^2/2k) = (9.69 \times 10^4 \text{ K})b_{40}^2$ for pure thermal broadening with $b = (40 \text{ km s}^{-1})b_{40}$. Owing to the large abundance of hydrogen, a small neutral fraction (HI) remains detectable in Ly α up to $T \sim 10^6$ K, although high S/N is required to measure the broad, shallow absorption. As a result, the surveys of BLAs differ considerably. In their survey of seven active galactic nucleus (AGN) sight lines, Lehner et al. (2007) found a BLA frequency of dN/dz = 30 ± 4 for absorbers with 40 km s⁻¹ $\leq b \leq 150$ km s⁻¹ and $\log N_{\rm H_{I}} \ge 13.2$. They claimed that 20% of the baryons reside in BLAs. A more recent survey (Danforth et al. 2010) came to different conclusions. Surveying BLA candidates along seven AGN sight lines observed by HST/STIS, their BLA absorption-line frequency per unit redshift was $dN/dz = 18 \pm 11$, comparable to that of the O vI absorbers but 40% lower than that found by Lehner et al. (2007). After correction for possible (20%–40%) overlap between BLA and O vI (metal-bearing) absorbers, the corresponding baryon fraction is $\Omega_{\text{BLA}}/\tilde{\Omega}_b = 0.14^{+0.024}_{-0.018}$. For Figure 10, we adopt a value of $14\% \pm 7\%$, with an increased error reflecting the uncertain detection statistics. We apply their metallicity-based correction to obtain a blended total (approximately 1/4 overlap) of $25\% \pm 8\%$ for the O VI/BLA-traced WHIM.
- 4. WHIM (X-ray-absorber-traced). Our simulations (Figure 3) and those of Cen (2012) suggest that ~15% of the baryons could be contained in hotter WHIM, at $T > 10^6$ K. Some of this gas could be detectable in X-ray absorption lines of trace metals (O VII, O VIII, Ne IX, Ne X, etc.). However, most of these weak absorption lines are below the detection limits of current X-ray spectrographs (Yao et al. 2012). The suggested absorption systems are too few in number to provide good statistics, and many are unconfirmed.
- 5. *Galaxies*. Salucci & Persic (1999) found that galaxies contribute 7% of the baryons. More recent discussion by Fukugita & Peebles (2004) estimated 6%. In Figure 10, we assume that galaxies contribute $7\% \pm 2\%$ of the baryons.
- Groups and clusters. The integrated cluster mass function of Bahcall & Cen (1993) was used by Fukugita et al. (1998) to find that the baryon contribution of clusters of galaxies

consists of $\Omega_b^{(\text{stars})} = 0.00155 h^{-1.5}$ and $\Omega_b^{(\text{gas})} = 0.003 h^{-1}$. Adjusting for h = 0.7, we find a cluster contribution of $\Omega_b^{(\text{cl})} = 0.00308$ or 6.8% of the baryons. Fukugita & Peebles (2004) revised the hot-baryon contribution to $\Omega_b^{(\text{cl})} = 0.0018 \pm 0.0007$ or 4% of the baryons, owing to a redefinition of cluster mass (Reiprich & Böhringer 2002). For the total contribution of galaxy clusters, including their hot gas, we adopt a fraction $4.0\% \pm 1.5\%$ of the baryons.

- 7. Cold H I (and He I) Gas. Zwaan et al. (2003) and Rosenberg & Schneider (2003) conducted blind HI surveys in the 21 cm line that probe the mass density in neutral atomic gas. The HIPASS survey (Zwaan et al. 2003) found $\Omega_{\rm HI} = (4.7 \pm 0.7) \times 10^{-4}$. Following the discussion of Fukugita & Peebles (2004), which augments the HI measurements by the expected accompanying cold He I and H₂, we plot the total cold gas mass in Figure 10 as $1.7\% \pm 0.4\%$ of the baryons.
- 8. CGM. X-ray spectra of AGNs taken with both Chandra and *XMM-Newton* detected strong O vII absorbers at $z \approx 0$ (see Bregman 2007; McKernan et al. 2005; Wang et al. 2005; Fang et al. 2006). The typical detected column densities, $N_{\rm O\, v II} \approx 10^{16} \, {\rm cm}^{-2}$, correspond to ionized hydrogen column densities $N_{\rm H\, II} \approx 10^{20} \, {\rm cm}^{-2}$ assuming a length scale ~ 10 kpc and mean metallicity of 20% solar. Several arguments suggest that the Galactic O VII resides in a thick disk or low scale length halo (5-10 kpc; see Yao & Wang 2005). Such a reservoir holds $\sim 10^9 M_{\odot}$ which is $\sim 2\%$ of the 5 \times 10¹¹ M_{\odot} in Milky Way baryons. Bregman (2007) suggested that a hot gaseous medium with mass $\sim 10^{10} M_{\odot}$ might extend throughout the Local Group. Such a reservoir is also $\sim 2\%$ of the 6 \times 10¹¹ M_{\odot} baryonic mass of the Local Group, assuming total mass $5 \times 10^{12} M_{\odot}$ and 12% baryon fraction (McGaugh et al. 2010). However, the Milky Way halo and Local Group may not be typical of other star-forming galaxies. Recent COS studies of 42 galaxies (Tumlinson et al. 2011) found that large (150 kpc) oxygenrich halos of star-forming galaxies are major reservoirs of galactic metals. Additional CGM could extend to distances of 100-200 kpc from galaxies with higher specific SFRs (Stocke et al. 2006). Savage et al. (2010) detected hot circumgalactic gas (log T = 5.8-6.2) in HI-free OVI absorption associated with a pair (perhaps small group) of galaxies at $z \approx 0.167$, at impact parameters $p \approx 100$ kpc. They note that the absence of HI absorption with broad O VI suggests a "rare but important class of low-z intergalactic medium absorbers."

Prochaska et al. (2011) took this idea further, suggesting that all the O VI arises in the "extended CGM of sub- L^* galaxies." Their mass estimate associates the O vI absorption with H I around galaxies $(0.1 < L/L^* < 1)$ having constant hydrogen column densities, $N_{\rm H} = 10^{19} \, {\rm cm}^{-2}$, over the full 200-300 kpc extent, as gauged by AGN-galaxy impact parameters. They estimated that these extended halos could contain a mass $M_{\rm CGM} \approx (3 \times 10^{10} M_{\odot}) (r_{\rm CGM}/300 \rm kpc)^2$, which would represent $\sim 50\%$ of the baryon masses of present-day sub- L^* galaxies. They further assert that gas at these large distances is gravitationally bound and virialized. We question the realism of constant-N, virialized gas at such large distances from dwarf galaxies. Previous nearest-neighbor studies of low-z O vi absorbers and galaxies (Stocke et al. 2006; Wakker & Savage 2009) found correlations with L^* galaxies (at 800 kpc) and with dwarf (0.1 L^*) galaxies (at 200 kpc). For Figure 10, we adopt a CGM contribution of $5\% \pm 3\%$, recognizing that the CGM reservoir is still poorly understood.

4.2. Error Budgets

Here, we summarize the current status of the error budgets for the major contributors to uncertainty in the diffuse Ly α forest baryon census. Many of the parameters enter the formula for $\Omega_b^{(H_1)}$ as the square root, a weak dependence (see Equation (6)) arising because recombination theory predicts that $N_{H_1} \propto n_H^2$ for highly ionized absorbers. Thus, the total baryon mass (proportional to n_H) depends on a weight factor $N_{14}^{1/2}$. From this formulation, we can conduct an error-propagation analysis to arrive at the overall uncertainty on the Ly α contribution to Ω_b in Equation (9). This quantity depends on five parameters, which we list below with assigned errors.

- 1. Distribution of H I column densities. Danforth & Shull (2008) measured the distribution of H I column densities, $dN/dz \propto N_{\rm H1}^{-\beta}$. Based on 650 low-redshift Ly α absorbers, they found a slope $\beta = 1.73 \pm 0.04$ and a baryon content of 29% $\pm 4\%$ of Ω_b , integrated over 12.5 $\leq \log N_{\rm H1} \leq 16.5$. Our new survey (Tilton et al. 2012) finds $\beta = 1.68 \pm 0.03$ and a contribution of 28% $\pm 4\%$ from the Ly α forest plus partial Lyman-limit systems to the baryon fraction. We assume 15% uncertainty in the column-density distribution statistics, which are increasingly uncertain at $\log N_{\rm H1} < 13.0$. Extending the $N_{\rm H1}^{-1.7}$ distribution from $\log N = 12.5$ –12.0 would add another 3% to the baryon fraction (from 28% to 31%) if there is no change in slope.
- 2. Hydrogen photoionization rate. This rate, $\Gamma_{\rm H}$, depends on the radiation field normalization at 1 ryd (I_0) and spectral slope (α_s) between 1.0–1.5 ryd. Previous AGN composite spectra found indices ranging from $\alpha_s = 1.76 \pm 0.12$ (Telfer et al. 2002) to $\alpha_s = 0.56^{+0.38}_{-0.28}$ (Scott et al. 2004). New *HST*/COS composite spectra of AGNs find an index $\alpha_s = 1.59 \pm 0.20$ (Shull et al. 2012b), close to the Telfer et al. (2002) value for radio-quiet AGNs. Our calculations also take into account the $(1 + z)^{4.4}$ rise in $\Gamma_{\rm H}(z)$ from z = 0to z = 0.7, a fit to the recent calculations of Haardt & Madau (2012). We estimate the joint error on $\Gamma_{\rm H}$ as $\pm 50\%$ from models of the metagalactic radiation field from quasars and galaxies (Shull et al. 1999; Haardt & Madau 2012).
- 3. Characteristic scale length of absorbers. The characteristic impact parameter, p_{100} , at $N_{\rm H_{I}} \approx 10^{14} \rm ~cm^{-2}$ in units of 100 kpc, is inferred by direct and indirect means, including comparing "hits and misses" of Ly α absorbers along nearby sight lines (Bechtold et al. 1994) and the cumulative distributions of absorbers with nearest-neighbor galaxies (Stocke et al. 1995; Shull et al. 1998). The frequency of Ly α absorber cross sections, when associated with the space density of galaxies down to luminosities $L \approx 0.01-0.03 L^*$ (Shull et al. 1996; Stocke et al. 2006; Prochaska et al. 2011). We adopt an uncertainty of $\pm 50\%$ on p_{100} .
- 4. Electron temperature. Temperature (T_e) enters through the square root of the hydrogen recombination rate coefficient, $\alpha_{\rm H}^{\rm (A)} \propto T^{-0.726}$. Models of IGM photoelectric heating (Donahue & Shull 1991) predict a range from 5000 K to 30,000 K. For z < 0.4, with small expected variations from photoionization, we adopt an uncertainty of $\pm 30\%$.

5. *Hubble constant.* This parameter has been measured as $H_0 = 72 \pm 8 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Freedman et al. 2001) and $H_0 = 73.8 \pm 2.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Riess et al. 2011), using distance scales based on Cepheids in galaxies with Type Ia supernovae. To be conservative, we adopt an error of $\pm 5\%$.

From standard error-propagation formulas, we write the relative error on $\Omega_b^{(\text{H}_{\text{I}})}$ as the quadrature sum of relative errors on the five parameters, weighted by the square of the exponents (1, 0.5, or 0.363) as they appear in the scaling (see Equation (9)):

$$\left(\frac{\sigma_{\Omega}}{\Omega}\right)^2 = \left(\frac{\sigma_N}{N}\right)^2 + \left(\frac{\sigma_h}{h}\right)^2 + \left(\frac{\sigma_N}{N}\right)^2 + (0.5)^2 \\ \times \left[\left(\frac{\sigma_{\Gamma}}{\Gamma}\right)^2 + \left(\frac{\sigma_p}{p}\right)^2\right] + (0.363)^2 \left(\frac{\sigma_T}{T}\right)^2.$$
(10)

This formula gives a relative error $(\sigma_{\Omega}/\Omega) = 0.40$, so that we can express $\Omega_b^{(\text{H}_{\text{I}})}/\Omega_b^{(\text{tot})} = 0.28 \pm 0.11$. Most (77%) of the error budget comes from uncertainties in the ionizing radiation field (Γ_{H}) and characteristic absorber size (p_{100}) .

5. CONCLUSIONS AND FUTURE SURVEYS

What observations and theoretical work are needed to make progress on the baryon census, both in sensitivity and in accuracy? First, we need more precise UV absorption-line surveys to measure O vI and Ly α absorbers to lower column densities. As described in Section 3, the numbers of absorbers in current surveys become increasingly uncertain at column densities $\log N_{\rm H_{I}} < 13.0$ and $\log N_{\rm O_{VI}} < 13.5$. The current surveys integrate below these levels, but our experience using COS to re-examine earlier Ly α and O vI detections with *FUSE*, GHRS, and STIS, suggests that some of these weak absorbers are unconfirmed with high-S/N data. In our HST Archive Legacy Project, Tilton et al. (2012) re-analyzed O vI and Ly α data from HST/STIS to provide critically evaluated column densities for $N_{\rm H\,I}$ and $N_{\rm O\,VI}$, and their absorption-line frequencies, $d\mathcal{N}/dz$. The new O vI data were included, together with our fits to $f_{\rm O\,VI}(Z/Z_{\odot})$, to yield more accurate values of $\Omega_h^{\rm (O\,VI)}$

With the 10-fold increase in UV sensitivity of COS on *HST*, we should be able to do even better. We hope to use HST/COS to obtain high-quality data (S/N \ge 30) to search for additional baryons in weak absorbers and constrain the predicted flattening in the column density distributions of HI and OVI. Scaled to column densities $(10^{13} \text{ cm}^{-2})N_{13}$, these lines have equivalent widths of $(12.5 \text{ mÅ})N_{13}$ for O VI $\lambda 1032$ and (54.5 mÅ) N_{13} for Ly α . These weak-absorber surveys will require HST/COS sensitivity to 4 mÅ equivalent widths, which is achievable at S/N = 30 toward many bright AGN background targets. We can also use COS to obtain better detections and statistics for BLAs and the NevIII doublet $(\lambda\lambda770.4, 780.3)$. The Ne VIII lines are potentially more reliable probes of hot, collisionally ionized gas than O vi, since Ne vIII requires 207 eV to produce and is likely to be less contaminated by photoionization. The lower solar neon abundance, $(Ne/O)_{\odot} \approx 0.15$, makes the Ne VIII lines weak, and redshifts z > 0.47 are needed to shift them into the *HST*/COS band. The BLAs have considerable promise for WHIM probes, as they do not require corrections for metallicity. They do require determining the neutral fraction, $f_{\rm HI}$, through careful modeling of the gas temperature and ionization conditions.

It would also be helpful to verify the claimed X-ray detections of O vII in the WHIM (Nicastro et al. 2005a, 2005b) which are not confirmed in other data (e.g., Kaastra et al. 2006; Rasmussen et al. 2007) or in re-analysis of the same data (Yao et al. 2012). The most critical observations for the WHIM census may require a next generation of X-ray spectrographs to measure the weak absorption lines of O VII λ 21.602, O VIII λ 18.969, and other He-like and H-like lines of abundant metals (C v, C vI, N VI, N VII). As discussed by Yao et al. (2012), this requires high-throughput spectrographs ($E \approx 0.3-1.0$ keV) with energy resolution $E/\Delta E > 4000$ sufficient to resolve O VII absorbers with mÅ equivalent width. For weak lines, the predicted O VII equivalent widths are $W_{\lambda} = (2.88 \text{ mÅ}) (N_{O VII}/10^{15} \text{ cm}^{-2})$.

Finally, the IGM simulations can be improved in several aspects, in order to use them as more reliable predictors of IGM parameters. In this paper, we computed individual (cell-by-cell) values of metallicity Z and ionization fractions, $f_{\rm H\,I}$ and $f_{\rm O\,VI}$, together with their statistical variations and covariance. Our simulations (Smith et al. 2011) were performed with somewhat larger box sizes (50 h^{-1} Mpc) and on a larger 1024³ grid compared with previous studies of low-z IGM thermodynamics. Our O vI conclusions appear to be robust, as gauged by convergence tests and runs with different methods of injecting feedback from star formation into the grid. Post-processing these simulations allowed us to provide more accurate corrections for the product $(Z/Z_{\odot}) f_{O_{VI}}$ as a function of column density $N_{O_{VI}}$. These statistics can be performed for other key ions (O VII, Ne VIII). We will extend our simulations through higher resolution, addition of discrete ionizing sources, and radiative transfer. We also will explore the correct mixture of collisional ionization and photoionization in the WHIM, a project that requires understanding the implications of different feedback mechanisms for injecting mass, thermal energy, and metals into the CGM. How these metals mix and radiate likely determines the thermodynamics of the surrounding IGM. Because there still exist considerable differences between how simulations treat the thermal state of the IGM, we will continue to push to higher resolution to capture the low-mass galaxies which are important for metal production and mass injection.

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