

The Baryon Census in a Multiphase Intergalactic Medium

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In this white paper, we summarize the current observations of the baryon census at low redshift (Shull, Smith, & Danforth 2012). We then suggest improvements in measuring the baryons in major components of the IGM and CGM with future UV and X-ray spectroscopic missions that could find and map the missing baryons, the fuel for the formation and chemical evolution of galaxies.

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 low-redshift universe (Fukugita, Hogan, & Peebles 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* (WMAP) found that baryons comprise a fraction $\Omega_b = 0.0455 \pm 0.0028$ of the critical matter-energy density of the universe, $\rho_{\text{cr}} = (9.205 \times 10^{-30} \text{ g cm}^{-3})h_{70}^2$, where h_{70} is the Hubble constant (H_0) in units of $70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. This corresponds to a comoving hydrogen number density (at redshift $z = 0$) of only $n_H = (1.9 \times 10^{-7} \text{ cm}^{-3})h_{70}^2$.

An inefficient distribution of collapsed baryons vs. distributed matter is a prediction of nearly all cosmological simulations (see Figure 1a) of large-scale structure formation (Cen & Ostriker 1999, 2006; Davé et al. 1999, 2001; Smith et al. 2011; Tepper-Garcia 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 ($\Delta_b = \rho_b/\bar{\rho}_b$) and temperature (T). In fact, a 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. Together, these processes affect the rate of accretion onto galaxies (cold-mode or hot-mode) and control the process of galaxy and star formation.

Unfortunately, the observed baryon inventories in the low redshift universe are uncertain. Theoretical estimates of the physical state of the gas are complicated by the formation

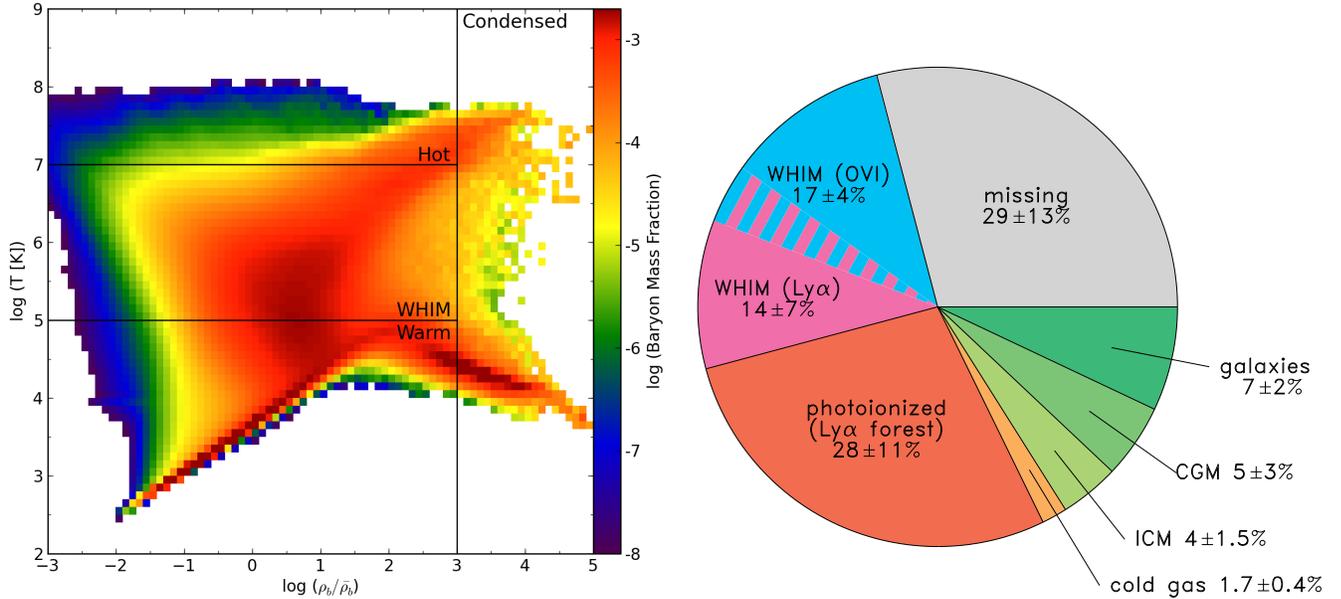


Fig. 1.— Figures from recent study by Shull, Smith, & Danforth (2012). (Left) Simulated distribution of IGM in temperature T and baryon overdensity $\Delta_b = \rho_b/\bar{\rho}_b$, color-coded by baryon mass fraction. Distribution shows the thermal phases, commonly labeled as warm (diffuse photoionized gas), WHIM, and condensed. (Right) Compilation of current observational measurements of the low-redshift baryon census. Slices of the pie-chart show baryons in collapsed form, in the circumgalactic medium (CGM) and intercluster medium (ICM), and in cold gas (H I and He I). The primary baryon reservoirs include diffuse photoionized Ly α forest and WHIM traced by O VI and broad Ly α absorbers. Collapsed phases (galaxies, CGM, ICM, cold neutral gas) total $18 \pm 4\%$, and $29 \pm 13\%$ of the baryons remain unaccounted for. An additional 15% may reside in X-ray absorbing gas at $T \geq 10^{6.3}$ K. Even more baryons may be found in weaker lines of low-column density O VI and Ly α absorbers. Deeper spectroscopic UV and X-ray surveys are required to find and characterize this IGM and CGM, gas that provides fuel for new stars and galaxy formation.

of galaxies and large-scale structure and the 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; Fukugita & Peebles 2004). Over the last 15 years, substantial reservoirs of gas have also been found in the intergalactic medium (IGM), in the halos of galaxies, and in the circumgalactic medium (CGM), including metal-enriched gas blown out of galaxies (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 (Bregman 2007; Danforth & Shull 2008) including the warm-hot IGM (or WHIM). Ultraviolet spectroscopic surveys of Ly α and O VI have identified substantial numbers of absorbers (Danforth & Shull 2008; Tripp et al. 2008; Thom & Chen 2008), but claimed detections of hotter in X-ray absorption by O VII (Nicastrò et al. 2005a,b) 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.

Observations (Figure 1b) of the “Lyman- 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 10^5 K to 10^7 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 (C IV, N V, O VI), extreme ultraviolet (O IV, O V, Ne VIII), and soft X-ray (O VII, O VIII, 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 $-6.6 < \log f_{\text{HI}} < -4.8$. 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 2008; Tripp et al. 2008; Thom & Chen 2008), which probe the temperature range $10^{5.3-5.7}$ K in collisionally ionized gas. Tilton et al. (2012) measured the column densities of 111 O VI absorbers and estimated that $17 \pm 4\%$ of the baryons reside in this phase, assuming new correction factors for the metallicity and O VI ionization fraction (Shull et al. 2012). 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 $\log T > 6$ requires X-ray searches for trace metal absorption lines from highly ionized C, O, or Ne. Their 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 $\lambda 21.602$ (Nicastrò et al. 2005a,b, 2008; Buote et al. 2009; Fang et al. 2010; Zappacosta et al. 2010)

and hydrogenic O VIII $\lambda 18.969$ (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-S/N data from the Cosmic Origins Spectrograph (COS) on the *Hubble Space Telescope* (*HST*) or in O VII (Yao et al. 2012) in *Chandra* data.

Figure 1b 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. The slices show contributions, $\Omega_b^{(i)}/\Omega_b^{(\text{tot})}$, to the total baryon content from components (i). Measurements of Ly α , O VI, and broad Ly α absorbers, together with more careful corrections for metallicity and ionization fraction, can now account for $\sim 60\%$ of the baryons in the IGM. An additional 5% may reside in circumgalactic gas, 7% in galaxies, and 4% clusters. *This still leaves a substantial fraction, $29 \pm 13\%$, unaccounted for.*

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. The numbers of absorbers in current surveys become increasingly uncertain at column densities $N_{\text{HI}} < 10^{13.0} \text{cm}^{-2}$ and $N_{\text{OVI}} < 10^{13.5} \text{cm}^{-2}$. Finding and mapping this IGM/CGM fuel supply will require new generation of spectrographs, optics, and high-precision detectors on a larger telescope ($D \geq 4^{\text{m}}$ aperture). These weak-absorber surveys will require sensitivity to 2 mÅ equivalent widths, which is achievable at S/N = 50 toward many bright AGN background targets. We also need to obtain better detections and statistics for broad Ly α absorbers (BLAs) and the Ne VIII doublet (770.4, 780.3 Å). 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. Redshifts $z > 0.47$ are needed to shift these EUV lines into the *HST*/COS band, but new far-UV missions with sensitivity down to 1000 Å would open up many more AGN targets at $z > 0.30$. The BLAs also have considerable promise for WHIM probes, as they do not require corrections for metallicity. They do require determining the neutral fraction, f_{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, most of which are not confirmed. These new observations will allow us to explore the 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.

The most critical observations for the WHIM census will 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 $m\text{\AA}$ equivalent width. For weak lines, the predicted O VII equivalent widths are $W_\lambda = (2.88 m\text{\AA})(N_{\text{OVII}}/10^{15} \text{ cm}^{-2})$.

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