Missing Baryons in the Warm-Hot Intergalactic Medium

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Abstract. This review briefly discusses the use of UV absorption lines in the spectra of low-redshift QSOs for the study of the physical conditions, metallicity, and baryonic content of the low-z IGM, with emphasis on implications for the missing baryons problem. Current results on the statistics and baryonic content of intervening, low-z O VI and Lyα absorption-line systems are presented with some comments on overlap between these two classes of absorbers and consequent baryon double-counting problems. From observations of a sample of 16 QSOs observed with the E140M echelle mode of STIS, we find 44 intervening O VI absorbers and 14 associated O VI systems (i.e., systems with z_{abs} ≈ z_{em}). This sample implies that the number of intervening O VI absorbers per unit redshift is dN/dz(O VI) = 23 ± 4 for lines with rest equivalent width > 30 mA. The intervening O VI systems contain at least 7% of the baryons if their typical metallicity is 1/10 solar and the O VI ion fraction is ≤0.2. This finding is consistent with predictions made by cosmological simulations of large-scale structure growth. Recently, a population of remarkably broad Lyα lines have been recognized in low-z quasar spectra. If the breadth of these Lyα features is predominantly due to thermal motions, then these HI absorbers likely harbor an important fraction of the baryons. We present and discuss some examples of the
broad Ly$\alpha$ absorbers. Finally, we summarize some findings on the relationships between O VI absorbers and nearby galaxies/large-scale structures.

1. Introduction

It is important to understand the distribution, physical conditions, and metallicity of the baryons in the Universe, both as a function of redshift (i.e., time) and as a function of environmental factors (e.g., proximity to galaxies, galaxy groups/clusters, or voids). Ordinary baryonic matter plays a fundamental role in galaxy formation and evolution, and the state of the baryons often provides a stringent test of cosmological theories. Measurements of deuterium abundances in low-metallicity QSO absorption systems (e.g., Burles & Tytler 1998; O’Meara et al. 2001; Sembach et al. 2004a) and observations of the cosmic microwave background (e.g., Spitzer et al. 2003) provide good estimations of the total quantity of baryons expected to be found in the Universe; expressed as the usual units of the closure density, these measurements indicate that $\Omega_b h^2 = 0.04$. At high redshifts, it appears that the matter in the Ly$\alpha$ forest can account for the majority of the expected baryons (Weinberg et al. 1997; Rauch et al. 1997; Schaye 2001), but attempts to inventory the baryons in the nearby Universe generally fail to find enough ordinary matter in the form of stars, hot (X-ray emitting) gas in clusters, and cold gas (see Fukugita et al. 1998, and references therein); the sum of these well-observed baryon reservoirs appears to be at least a factor of 2 lower than the predicted amount at the present epoch.

A variety of solutions to this “missing baryons” problem have been proposed, and considerable observational effort is currently being invested to test these ideas. One possible solution has emerged from hydrodynamic simulations of cosmological structure growth. These simulations predict that at high redshifts, all of the baryons were indeed in the cool, photoionized Ly$\alpha$ forest, but as time passed, much of that matter collapsed and turned into galaxies, and much of the Ly$\alpha$ forest that didn’t turn into stars was shock heated into the $10^5 - 10^7$ K temperature range. In these models, at the present time the $10^5 - 10^7$ K baryons remain located in the low-density intergalactic gas, the so-called “warm-hot intergalactic medium” (WHIM or WHIGM).\footnote{In this paper we use the WHIGM (pronounced “wiggum”) acronym because “WHIM” can be confused with “WIM”, the well-known and widely-studied warm ionized medium phase of galactic interstellar media.} As shown in Figure 1, many different CDM cosmological simulations robustly make the same prediction with regard to baryonic content of the WHIGM: currently, roughly 1/3 of the baryons are in stars in galaxies, 1/3 remain in the shock-heated WHIGM, and 1/3 remain in the cool photoionized Ly$\alpha$ forest (Cen & Ostriker 1999; Davé et al. 2001, and references therein). Since the WHIGM result reproducibly emerges from a diverse set of cosmological simulations, observational evidence that a significant portion of the baryons are located in the low-$z$ WHIGM would therefore not only solve the long-standing missing baryons problem and provide important constraints for galaxy evolution modeling, this would also indicate that at least...
in some regards, the cosmological simulations are able to capture enough of the IGM physics adequately to make correct predictions.

2. Statistics and Baryonic Content of Low-z O VI Absorbers

Due to its low density and temperature range, the WHIGM is expected to be exceedingly difficult to detect in emission. Absorption spectroscopy provides a much more sensitive means to study low-density gas, and in the near term this technique is likely to provide the primary observational constraints on the low-redshift WHIGM. In the ultraviolet, the resonance line doublet of Li-like O VI at 1031.93 and 1037.62 Å is particularly useful for WHIGM observations because (1) in collisional ionization eq., O VI peaks in abundance at log $T \approx 5.5$, (2) oxygen is the most abundant metal, and (3) the lines have relatively large $f$-values.

To search for low-$z$ O VI absorbers and the missing baryons, we have been observing low-redshift QSOs for several years with both the Space Telescope Imaging Spectrograph (STIS) and the Far Ultraviolet Spectroscopic Explorer (FUSE). These observations have revealed a large number of intervening and associated (i.e., $z_{\text{abs}} \approx z_{\text{QSO}}$) O VI systems. Examples of the detected O VI lines are shown in Figures 2 and 3. The first QSO that we observed for this purpose (H1821+643, shown in Figure 2) unveiled a surprisingly large number of intervening systems (Tripp, Savage, & Jenkins 2000; Oegerle et al. 2000). The detection of six intervening O VI absorbers toward H1821+643 indicated
Figure 2. **Upper panel:** STIS E140M echelle spectrum of H1821+643 with the Lyα, N V, and O VI emission lines of the QSO marked. **Lower panels:** examples of the O VI λλ1031.93, 1037.62 doublet in absorption including (lower left) the intervening absorption systems at \(z_{\text{abs}} = 0.22497\) and 0.22636, and (lower right) the multicomponent associated absorber (i.e., \(z_{\text{abs}} \approx z_{\text{QSO}}\)) at \(z_{\text{abs}} = 0.29672\). The upper panel is binned, but the lower panels show the spectrum at full, unbinned resolution \((\text{FWHM} = 7 \text{ km s}^{-1})\).
Figure 3. Examples of intervening O VI absorbers detected with *FUSE* in the spectra of PG0953+415 (upper panel, see Savage et al. 2002) and 3C 273 (lower panel, see Sembach et al. 2001) including the Lyβ and O VI λλ1031.93, 1037.62 lines at $z_{\text{abs}} = 0.06807$ (PG0953+415) and $z_{\text{abs}} = 0.12003$ (3C 273).
and an incidence of O VI systems per unit redshift \( dN/dz \approx 50 \) for lines with rest equivalent width \( W_r \geq 30 \) mÅ. Observations of other sight lines confirmed the redshift density of O VI lines at \( z < 0.6 \) (Tripp & Savage 2000; Savage et al. 2002; Richter et al. 2004, Sembach et al. 2004b; Prochaska et al. 2004). To estimate the baryonic content of the O VI systems, information (or assumptions) about the gas metallicity \((O/H)\) and O VI ionization fraction \( f(O\ VI)\) are required. However, since \( \Omega_b(O\ VI) \propto f(O\ VI)^{-1}(O/H)^{-1}\), it is possible to place useful lower limits on \( \Omega_b(O\ VI)\) by assuming the maximum plausible values for \( f(O\ VI)\) and \( (O/H)\). For O VI, the ion fraction rarely exceeds 0.2 (Tripp & Savage 2000), but it is less clear what the maximum (or even the typical) metallicity might be. Assuming \((O/H) = 0.1 (O/H)_{\odot}\) and \( f(O\ VI) \leq 0.2\), we find that low–z O VI absorbers harbor 5% or more of the baryons.

The baryonic content and \( dN/dz\) of the low–z O VI lines derived from the first observations are consistent with the predictions from a variety of cosmological simulations (Cen et al. 2001, Fang & Bryan 2001; Chen et al. 2003). However, the first observational papers suffered considerably from small-sample statistics. To rectify this problem, we have acquired additional observations of low–z QSOs with the E140M echelle mode of STIS. Combined with additional E140M data from the HST archive, we now have a sample of 16 QSOs with \( 0.1583 \leq z_{QSO} \leq 0.5726\). At the time of this writing, we have found 44 intervening O VI absorbers and 14 associated O VI systems in these spectra. We have carefully assessed the total redshift path probed by this sample (e.g., we have corrected the path to account for regions that are blocked by strong ISM or unrelated extragalactic lines, and we have accounted for S/N variations vs. \( \lambda \) for each sight line). With this substantially larger O VI sample, we find for the intervening systems \( dN/dz(O\ VI) = 23 \pm 4\) for lines with rest equivalent width \( > 30 \) mÅ. Again assuming \((O/H) = 0.1 (O/H)_{\odot}\) and \( f(O\ VI) < 0.2\), we obtain \( \Omega_b(O\ VI) = 0.0027\) or \( \Omega_b(O\ VI)/\Omega_b(\text{total}) \geq 0.068\), i.e., 7% of the baryons.

It is important to note that we have used the recent revision of the solar oxygen abundance reported by Allende Prieto et al. (2001) to determine the value of \((O/H) = 1/10 (O/H)_{\odot}\) for this calculation of \( \Omega_b(O\ VI)\). Our previous papers used \((O/H)_{\odot}\) from Grevesse & coworkers (e.g., Grevesse et al. 1996); the Allende Prieto et al. value for \((O/H)_{\odot}\) is substantially lower. Since \( \Omega_b(O\ VI) \propto (O/H)^{-1}\), the substantial reduction in the solar oxygen abundance reported by Allende Prieto et al. leads to an increase in \( \Omega_b(O\ VI)\). Taking into account the revision of \((O/H)_{\odot}\), the new constraints on \( \Omega_b(O\ VI)\) are in excellent agreement with the earlier findings. Our sample applies to systems with \( z_{\text{abs}} > 0.12\); we note that a largely independent sample of O VI systems at \( z_{\text{abs}} < 0.15\) compiled by Danforth & Shull (2004) yields very similar values for \( dN/dz\) and \( \Omega_b(O\ VI)\). We are continuing to add data to our sample, mainly by adding FUSE observations of the same sight lines, which provide information about O VI lines at \( z_{\text{abs}} < 0.13\).

3. Ionization and Metallicity of the O VI Absorbers

But what about the ionization and metallicity of the O VI systems? Is 1/10 solar metallicity an appropriate assumption, and moreover are the absorbers collisionally ionized as expected for the (shocked) WHIGM? Low–z absorption
systems appear to have a wide range of metallicities: some show very low abundances (e.g., Tripp et al. 2002; 2004) while others have attained $Z \geq 0.5Z_\odot$ (e.g., Savage et al. 2002, 2004; Jenkins et al. 2005). Likewise, some O VI systems appear to be photoionized by the UV background (e.g., Savage et al. 2002), but some O VI lines arise in collisionally ionized, hot gas (e.g., Tripp et al. 2001; Savage et al. 2004). Moreover, there is undeniable evidence that many O VI systems are multiphase entities (Tripp et al. 2000, 2001; Shull et al. 2003; Richter et al. 2004; Sembach et al. 2004b; Savage et al. 2004; Tumlinson et al. 2004). In the near term, the multiphase nature of the O VI systems complicates the interpretation of the absorbers, but ultimately the rich information in these cases will likely be very valuable for understanding their detailed nature.

4. Baryonic Content of Low-z Ly$\alpha$ Lines and Double Counting

What about baryons in the cool, photoionized Ly$\alpha$ clouds at low redshifts? There is good agreement regarding the statistics (e.g., $dN/dz$) of low$-z$ Ly$\alpha$ lines (compare Tripp et al. 1998; Penton et al. 2000a, 2004; Richter et al. 2004; Sembach et al. 2004b). To estimate the baryonic content of the Ly$\alpha$ absorbers, very large ionization corrections must be applied, but at least no metallicity information is needed. Estimations of the total baryonic mass in the low$-z$ Ly$\alpha$ forest (e.g., Shull, Stocke, & Penton 1996; Penton et al. 2000a, 2004) indicate that $\sim 30\%$ of the baryons are in these systems, in agreement with the cosmological simulations.

There is certainly overlap between O VI and Ly$\alpha$ absorbers, and this raises a concern about how to fold the contributions of the O VI and Ly$\alpha$ absorbers into the overall inventory of baryons: if some of the O VI systems are photoionized and have corresponding H I lines (e.g., Savage et al. 2002), then these baryons could be double-counted. However, it is probably also true that some of the Ly$\alpha$ lines which are assumed to arise in cool, photoionized gas actually originate in hot gas, so the double-counting problem operates in both directions. And, it is possible (even likely) that many systems contain a mix of hot and cool gas. We note that photoionized O VI systems are expected in the cosmological models (Cen et al. 2001; Fang & Bryan 2001). Solution of this problem will require large samples of absorbers with good-quality line measurements.

5. Broad Ly$\alpha$ Lines

Several papers have presented evidence of broad Ly$\alpha$ lines with $b$—values in excess of 40 km s$^{-1}$ (e.g., Tripp et al. 2001; Bowen, Pettini, & Blades 2002; Richter et al. 2004; Sembach et al. 2004b). Penton et al. (2004) have found broad Ly$\alpha$ lines as well but in some cases have mandated that these be fit with multiple components. Similarly, the automatic profile fitting algorithm used by Davé & Tripp (2001) forced the broad features to be fitted with multiple components. Some examples of broad Ly$\alpha$ lines are shown in Figure 4a; see Richter et al. (2004) and Sembach et al. (2004b) for additional plots of these broad H I lines. Figure 4b shows the $b$—values and H I columns for all Ly$\alpha$ lines identified by Richter et al. (2004) and Sembach et al. (2004b); this panel shows a significant population of strikingly broad lines. If the broadening of these lines
is predominantly due to thermal motions, then the implied temperature is in the WHIGM range, and their baryonic content is substantial (similar to the O VI systems). It remains possible that the breadth of these features is not due to the gas temperature. However, many of the broad Lyα lines are well-detected (see, e.g., Figure 7 in Sembach et al. 2004b) and cannot be instrument artifacts. While they could be continuum undulations intrinsic to QSO spectrum, this appears unlikely. A more likely explanation is that the broad Lyα lines are multiple, blended components as assumed in some of the papers above. Very high S/N spectra would be valuable for testing this possibility: if the lines are multiple blended features, departures from a simple Gaussian shape could be evident in high S/N data. We note that some of the broad Lyα lines presented in Sembach et al. (2004b) have good signal-to-noise and appear to be well-described by a single, smooth feature, i.e., there are no obvious indications of multiple components at the current signal-to-noise level (see Figure 7 in Sembach et al. 2004b). It would also be useful to compare the observed b vs. N(H I) (as in Figure 4b) to predictions from hydrodynamical simulations.
Figure 4. (Figure 4b) Doppler parameters and H I column densities of all Lyα identified in the spectra of PG1259+593 and PG1116+215 by Richter et al. (2004) and Sembach et al. (2004b); the solid line shows $b$ vs. $N$(H I) for a Gaussian line with 10% central optical depth. The right axis shows the temperature implied by the line width if the lines are due to a single, thermally-broadened component. In some cases, the smooth shape of the Lyα profile supports this assumption (see Figure 7 in Sembach et al. 2004b).
Figure 5. Comparison of Lyα and O VI absorber redshifts detected in the spectrum of PG1116+215 by Sembach et al. (2004b) to galaxy redshift measurements from the WIYN survey of Tripp, Lu, & Savage (1998). The upper portion shows the RA wedge and the lower shows Dec. In each wedge, Lyα line redshifts are indicated with vertical lines overplotted on the sight line while O VI line redshifts are shown with long lines offset from the sight line. Galaxies are shown with circles, and the size of the circle indicates proximity to the sight line: the largest circles mark galaxies with projected distances (ρ) less than 500 kpc from the line of sight; intermediate-size circles represent galaxies at 500 < ρ < 1000 kpc, and small circles show galaxies at ρ > 1 Mpc.
6. Relationships with Galaxies

Many papers have investigated the relationships between low−z Lyα lines and nearby galaxies/structures. A review of this literature is beyond the scope of this paper; a reasonable synopsis is that the majority of the low−z Lyα lines are strongly correlated with galaxies but a few are found in voids (e.g., Penton et al. 2000b; McLin et al. 2002), but despite the strong correlation, the detailed nature of the Lyα-galaxy relationship is not yet well-understood. The Lyα lines almost certainly have a variety of origins including (1) bound interstellar gas in the halo (or even disk) of individual galaxies, (2) tidally stripped debris, (3) galactic wind ejecta, and (4) truly intergalactic gas far from galaxies.

Our understanding of the OVI absorber-galaxy connection is even more immature, but already it is clear that the O VI systems are strongly correlated with galaxies as well. Several studies have revealed galaxies within a few hundred kpc from O VI systems (Savage, Tripp, & Lu 1998; Tripp et al. 2000; Tripp & Savage 2000; Chen & Prochaska 2000; Tripp et al. 2001; Savage et al. 2002; Shull et al. 2003; Sembach et al. 2004b; Tumlinson et al. 2004). As an example, Figure 5 compares the locations of galaxies found in the redshift survey of Tripp et al. (1998) to the redshifts of O VI and Lyα lines detected by Sembach et al. (2004b). Visual inspection of Figure 5 suggests that the OVI lines are correlated with the galaxies (see also Figure 21 in Sembach et al. 2004b for a striking visual comparison), and this is corroborated by statistical tests: Sembach et al. (2004b) find that the probability that the O VI absorbers are randomly distributed with respect to the galaxies shown in Figure 5 is $1.3 \times 10^{-4}$ to $2.0 \times 10^{-4}$ (depending on assumptions made). With the advent of powerful multiobject spectrographs on 8-10m telescopes, future studies of the nature of O VI absorbers (as well as other classes of absorption lines) and their connections with galaxies hold great promise for understanding the role and implications of these absorbers for galaxy evolution and cosmology.

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