Highly-Ionized Intergalactic Gas at Low Redshifts: Constraints from QSO Absorption Lines

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Abstract. High-resolution UV spectroscopy of low-$z$ QSOs with the Space Telescope Imaging Spectrograph and the Far Ultraviolet Spectroscopic Explorer has indicated that O VI absorption-line systems provide a valuable probe of the low-$z$ intergalactic medium. These observations and their implications are briefly reviewed. Though still uncertain due to the small sample, the number of O VI absorbers per unit redshift is quite high, and these absorbers appear to trace an important baryon reservoir. The O VI systems are intervening; they are highly displaced from the background QSO redshifts and are correlated with foreground luminous galaxies. Their physical conditions are variable and sometimes complicated. In some cases, there is clear evidence that the absorbers have a multiphase nature. Some appear to be photoionized by the UV background from QSOs, while others are probably collisionally ionized. However, the majority of the O VI lines have b-values that suggest an origin in collisionally ionized hot gas. The observations are in agreement with hydrodynamic simulations of cosmological structure growth, which predict substantial quantities of shock-heated, hot intergalactic gas at low $z$, but more observational and theoretical work is needed to confirm the nature of the O VI systems.

1. Introduction

Understanding the quantity, distribution, and physical state of the baryons in the universe is an important problem in current cosmology. Hydrodynamic simulations of cosmological structure growth predict that in the nearby universe, 30-50% of the baryons are in shock-heated intergalactic gas at $10^5 - 10^7$ K (Cen & Ostriker 1999; Davé et al. 2001). Gas with $T < 10^6$ K may be readily detected using O VI absorption lines in the spectrum of a background QSO. Observations with the Hubble Space Telescope Imaging Spectrograph (STIS) and the Far Ultraviolet Spectroscopic Explorer (FUSE) have recently revealed a surprising number of low-redshift O VI absorption line systems in the directions of a few QSOs, and the inferred high number of O VI systems per unit redshift suggests that these absorbers are indeed an important baryon reservoir. These observations and their implications regarding the physical nature and distribution of the intergalactic gas as well as its baryonic content are reviewed. This brief review attempts to collate results from collaborations with several groups involving major contributions from many people. Table 1 summarizes the pub-
lications from the first batch of QSOs that have been observed and provides some basic information on the intervening O VI lines detected in each sight line. After a few notes on the observations and data involved (§2), some comments are provided on the O VI absorber properties (§3), the baryonic content of these absorption systems (§4), and the ionization and physical conditions of the gas (§5). The paper is summarized in §6.

2. Observations

Table 1: Summary of First Detections of Low-z Intervening O VI Absorbers with STIS and FUSE

| Sight Line     | z_{QSO} | z_{abs}(O VI)^a | W_r (mÅ) | Class^c | Reference^d |
|---------------|---------|-----------------|----------|---------|-------------|
| PKS0405-123  | 0.573   | 0.16710         | 491±46   | Single-component | 1,2         |
|               |         | 0.18290         | 94±23    | Single-component | 1           |
|               |         | 0.36332         | 41±7     | (Single-component) | 1           |
|               |         | 0.49512         | 225±15   | Multicomponent   | 1           |
| PG0953+415   | 0.239   | 0.06807         | 127±9    | Single-component | 3           |
|               |         | 0.14232         | 112±12   | Single-component | 3,4         |
| 3C 273        | 0.158   | 0.12004         | 28±5     | Single-component | 5,1         |
| 3C 351        | 0.372   | 0.22110         | ...      | (Single-component) | 1           |
|               |         | 0.31656         | 230±14   | Multicomponent   | 1           |
| H1821+643    | 0.297   | 0.12120         | 90±17    | Single-component | 6,7         |
|               |         | 0.21326         | 38±9     | (Single-component) | 8           |
|               |         | 0.22497         | 185±9    | Multicomponent   | 8           |
|               |         | 0.22637         | 25±5     | Multicomponent^f | 8           |
|               |         | 0.24531         | 55±6     | Single-component | 8           |
|               |         | 0.26659         | 55±8     | Single-component | 8           |

^aHeliocentric absorption system redshift.
^bRest-frame equivalent width of the O VI λ1032 transition, the stronger line of the doublet. For FUSE observations, W_r is the mean of the measurements from the individual FUSE channels, each weighted inversely by its variance. Similarly, the weighted mean is reported for cases where the line is recorded independently in STIS and FUSE spectra.
^cO VI absorption lines which show clear evidence of component structure (such as the system shown in Figure 2) and which were consequently fitted with multiple components are referred to as multicomponent absorbers. O VI profiles adequately fitted with just one line are referred to as single-component systems. Parentheses indicate that the system is considered a “possible” O VI detection because only one line of the O VI doublet is detected; the other line is either lost in a blend or too weak to detect.
^dReference: 1. Tripp et al. (2002), 2. Chen & Prochaska (2000), 3. Savage et al. (2001), 4. Tripp & Savage (2000), 5. Sembach et al. (2001), 6. Tripp et al. (2001), 7. Oegerle et al. (2000), 8. Tripp, Savage, & Jenkins (2000).
^eA Lyman limit absorber showing many metal absorption lines is present at this redshift. However, the O VI λ1032 line is blended with a strongly saturated Milky Way Si II transition and cannot be measured. A well-detected line is present at the expected wavelength of the O VI λ1038 transition; this feature has W_r = 96±10 mÅ.
^fThis O VI doublet only shows one component (see Figure 1). However, it is only 340 km s^{-1} from the z_{abs} = 0.22497 absorber, and it is possible that all of these lines are all part of the same system. Consequently, this case is considered part of a multicomponent system.
Low-Redshift O VI Absorbers

Figure 1. Examples of intervening O VI absorbers detected in the STIS echelle spectra of PG0953+415 (left panels; see Tripp & Savage 2000) and H1821+643 (center and right panels; Tripp, Savage, & Jenkins 2000) plotted vs. rest-frame velocity ($v = 0$ at the $z_{abs}$ indicated in each panel). The velocities of galaxies near these absorbers and their projected distances from the sight line are indicated at the top of each panel.

The observations and data reduction procedures have been summarized in several papers (see references in Table 1). In brief, observations of the QSOs have been obtained with STIS (Kimble et al. 1998; Woodgate et al. 1998) and FUSE (Moos et al. 2000; Sahnow et al. 2000). The primary STIS observations employed the E140M echelle mode, which provides a resolution of $R = \lambda/\Delta\lambda = 46,000$ (7 km s$^{-1}$ FWHM) and wavelength coverage from $\sim$1150 to 1700 Å. Some first-order grating observations with STIS have also been obtained, primarily to search for corresponding C IV at longer wavelengths. FUSE has four co-aligned telescopes and Rowland spectrometers which record spectra on two microchannel plate detectors. Different coatings in the various FUSE channels enable spectral coverage from 905–1187 Å. The FUSE resolution is estimated to range from 17–25 km s$^{-1}$ (FWHM) depending on the wavelength and channel. Note that there is some overlap in the wavelength coverage of STIS and FUSE, and in a couple of cases O VI lines have been independently detected by both instruments.

We have also measured galaxy redshifts in the fields of several of the target QSOs with Hydra, the fiber-fed multiobject spectrograph on the WIYN telescope, in order to learn about the relationships between the low-$z$ absorbers and galaxies/environment. The observational and measurement techniques are
described in Tripp, Lu, & Savage (1998). A single Hydra setup covers a one-degree field of view; we usually surveyed a somewhat larger field by offsetting the field center for different fiber configurations.

3. O VI Absorber Properties

Some examples of O VI absorption lines (and detections, or lack thereof, of other species at the same redshift) are shown in Figures 1 and 2. Initial results on these absorption systems include the following:

The number of O VI absorbers per unit redshift \( dN/dz \) is remarkably high, and it is likely that these absorption systems trace an important baryon reservoir. However, the contribution to \( \Omega_b \) is still highly uncertain, and there are several outstanding issues, such as whether there is substantial double-counting in the baryon census due to overlap between O VI systems and plain Ly\( \alpha \) absorbers (see further discussion in §4).

The O VI absorbers are **intervening**. Excluding systems within 5000 km s\(^{-1}\) of the QSO redshift, the O VI systems are located close to luminous galaxies. Toward H1821+643, the five definite intervening O VI systems (Tripp et al. 2000, 2001) are within a projected distance of \( 1 \, h_{70}^{-1} \) Mpc or less of at least one galaxy with \( |\Delta v| = |c(z_{gal} - z_{abs})/(1 + z_{mean})| \leq 300 \) km s\(^{-1}\). In some cases,
multiple galaxies are close to the sight line (see, e.g., the top of Figure 1 or Figure 3 in Tripp et al. 2001). Combined with the large redshift difference from the QSO, this indicates that these are probably intervening systems that trace the large-scale gaseous environment in galaxy structures and the IGM rather than intrinsic absorbers which are sometimes ejected to remarkably large $\Delta v$ (Hamann & Ferland 1999, and references therein).

Similarly, Figure 3 shows the locations in redshift space of the O VI absorbers reported by Tripp & Savage (2000) and Savage et al. (2001) in the spectrum of PG0953+415 with respect to the observed galaxy distribution. Clearly, both the O VI and Lyα absorption lines follow the galaxy distribution. However, there are no galaxies particularly close to the O VI system at $z_{abs} = 0.06807$; the closest galaxy is at projected distance of 917 $h^{-1}_{75}$ kpc. This may be due to incompleteness of the galaxy redshift survey, but this is also predicted by the cosmological simulations, which find that the O VI absorbers arise in low-overdensity, unvirialized regions, i.e., the lines are expected to be found in large-scale galaxy filaments, but there may not be a galaxy very nearby (see, e.g., Cen et al. 2001).

The physical conditions and metallicities of the O VI absorbers are highly variable, and the conditions are frequently complex. In the intervening systems identified so far, the H I Lyα transition is always detected along with the O VI
T. M. Tripp

lines, as expected for gas with sub-solar metallicity which is collisionally ionized at $T < 10^6$ K or which is photoionized. In some cases these are the only detected absorption lines, but in other cases lines due to low and intermediate ionization stages (e.g., Si II, Si III, N V, C III, C IV) are also detected, usually in systems with higher H I column densities. The O VI/H I column density ratio varies substantially from system to system (e.g., Tripp et al. 2000); this may be due to significantly different metallicities, physical conditions, or both. Many systems show complicated component structure (see, e.g., Figure 1, Figure 2 in Tripp et al. 2000, or Figure 1 in Tripp et al. 2001), and there is often strong evidence that the absorbing media are multiphase. For example, the O VI and Si III absorption lines at $z_{\text{abs}} = 0.225$ toward H1821+643 (middle panels in Figure 1) cannot be explained by a single-phase absorber.

4. Baryonic Content

It has been noted for some time that there is a “missing baryon problem” at the present epoch: the well-observed baryon repositories in the nearby universe (e.g. Fukugita et al. 1998) fail to provide the quantity of baryons expected based on D/H measurements (e.g., Burles & Tytler 1998) or observations of the high−z Ly$\alpha$ forest (e.g., Rauch et al. 1997; Weinberg et al. 1997; Schaye 2001). As noted in §1, cosmological simulations suggest that the missing baryons are hidden in low-density regions of the IGM that have been shock-heated to $10^5 - 10^7$ K. Such gas can be revealed using QSO absorption lines such as the O VI or Ne VIII doublets (the O VI ion fraction peaks at $T \sim 300,000$ K), and this has been the primary motivation for the observations discussed in this paper.

The first STIS observations for this program (Tripp et al. 2000; Tripp & Savage 2000) suggested that the number of O VI systems per unit redshift is indeed interesting. Tripp et al. (2000) found $dN/dz \sim 50$ for $W_r > 30$ mÅ, albeit with large error bars. This is more comparable to $dN/dz$ of low−z Ly$\alpha$ absorbers than of other types of metal absorbers, as shown in Figure 4. We now have more observations, and Figure 4 summarizes the $dN/dz$ of O VI absorbers from more recent papers, as a function of the limiting equivalent width of the particular sample. The redshift density of other types of absorbers from the literature are also shown in Figure 4 for comparison. Figure 4 shows that $dN/dz$(O VI) appears to increase with decreasing limiting equivalent width, as predicted by cosmological simulations (Cen et al. 2001; Fang & Bryan 2001). However, more observations are needed to firmly establish this trend.

The high $dN/dz$ suggests that O VI systems are an important baryon reservoir. Following analogous calculations (e.g., Burles & Tytler 1996; Rao & Turnshek 2000), the baryonic content of the O VI absorbers, expressed in the usual

\footnote{Note that the Burles & Tytler (1996), Jannuzi & Weymann (2000), and the Mg II results apply to somewhat higher redshifts, and therefore this figure does not provide a completely fair comparison. However, Tripp et al. (2002) find that $dN/dz$(O VI) decreases with increasing limiting $W_r$ at lower redshifts as well.}
Figure 4. Number of absorbers per unit redshift ($dN/dz$) vs. limiting equivalent width of the sample for O VI, H I, and Mg II systems (as indicated in the key). Note that the Burles & Tytler and Jannuzi & Weymann measurements as well as the Mg II points were derived from somewhat higher redshift data, and $dN/dz$ is expected to depend on redshift. However, Tripp et al. (2002) find the $dN/dz$ of O VI systems decreases with increasing limiting equivalent width at the lowest redshifts as well.

fashion ($\Omega = \rho/\rho_c$), can be estimated using the following expressions:

$$\Omega_b(OVI) = \frac{\mu m_H H_0}{\rho_c c f(OVI)} \left( \frac{O}{H} \right)^{-1} \frac{\sum_i N_i(OVI)}{\sum_i \Delta X_i}$$

(1)

or, alternatively,

$$\Omega_b(OVI) = \frac{\mu m_H H_0}{\rho_c c f(OVI)} \left( \frac{O}{H} \right)^{-1} \frac{dN}{dOVI} \left( \frac{< N_{OVI}>}{(1 + z)} \right)$$

(2)

assuming $q_0 = 0$. Here $\Delta X_i$ is the absorption distance interval (e.g., Burles & Tytler 1996) probed to the $i^{th}$ sight line (corrected for spectral regions blocked by ISM or extragalactic lines), $\mu$ is the mean atomic weight, $(O/H)_{OVI}$ is the mean oxygen abundance by number, $< N_{OVI}>$ is the mean O VI column density of
the sample, and $f$(O VI) is the ion fraction. Values for $(O/H)_{O \text{ VI}}$ and $f$(O VI) must be assumed, but a conservative result can be obtained by assuming the largest plausible values for these parameters thereby minimizing $\Omega_{b}(O \text{ VI})$. In this way, Tripp et al. (2000) derived $\Omega_{b}(O \text{ VI}) \geq 0.004h_{75}^{-1}$ for a sample with $W_r \geq 30$ mÅ, assuming a mean metallicity of 1/10 solar and $f$(O VI) = 0.2. Similarly, Tripp & Savage (2000) obtained $\Omega_{b}(O \text{ VI}) \geq 0.003h_{75}^{-1}$ for a sample with $W_r \geq 60$ mÅ. These lower limits are comparable to the cosmological mass density in the form of stars, cool neutral gas, and X-ray emitting cluster gas at the present epoch (Fukugita, Hogan, & Peebles 1998).

However, there are several issues and sources of uncertainty. First, the results have large error bars due to the small size of the initial samples; using eqn. 2, Tripp & Savage (2000) obtained $\Omega_{b}(O \text{ VI}) \geq 0.003^{+0.004}_{-0.002}h_{75}^{-1}$ at the 1σ level. Therefore it may not be too surprising that more recent estimates of $\Omega_{b}(O \text{ VI})$ with larger samples yield somewhat smaller values: Savage et al. (2001) find $\Omega_{b}(O \text{ VI}) \geq 0.002h_{75}^{-1}$ with a limiting equivalent width of 50 mÅ, for example. Second, the blocking of some regions of the spectrum by unrelated lines (e.g., due to the Milky Way ISM) reduces the redshift path probed for O VI lines. The blocking correction affects $\Omega_{b}(O \text{ VI})$ because reducing $\Delta z$ (and $\Delta X$ in eqn. 1) increases $dN/dz$ and $\Omega_{b}(O \text{ VI})$. In the initial papers, we used a very simple algorithm to estimate this blocking correction. Any strong line that obscured either the O VI λ1032 or λ1038 lines reduced the total $\Delta z$. This is conservative and simple, but since we are using a doublet, a more accurate blocking correction can be obtained by checking for the other line of the doublet. If a particular strong line masks λ1032 at some redshift, a corresponding λ1038 feature should be present at the same $z$ (and vice versa). If no corresponding feature is evident, then the strong line does not block an O VI system. A more accurate assessment of blocking increases $\Delta z$ and decreases $\Omega_{b}(O \text{ VI})$, but the change is less than a factor of 2. Third, the mean metallicity of the absorbers may be higher than $0.1Z_{\odot}$. However, this is countervailed by the fact that $f$(O VI) is almost certainly less than 0.2. From their cosmological simulations, Cen et al. (2001) find $f$(O VI)/(Z/Z_{\odot}) $\sim$ 0.01 for a collisionally ionized O VI absorber with a 50 mÅ λ1032 line. This is a factor of $\sim$2 lower than the value we have assumed [reducing $f$(O VI)/(Z/Z_{\odot}) increases $\Omega_{b}(O \text{ VI})]. Fourth, there is a concern about double-counting in the baryon census. The contribution of low-$z$ Lyα absorbers to the baryon inventory has been estimated (Penton et al. 2000). These absorbers are assumed to be photoionized and relatively cool ($T \sim 10^4$ K). However, in the hydrodynamic simulations, some Lyα lines arise in substantially hotter gas (see Figure 4 in Davé & Tripp 2001). Likewise, some O VI systems could be photoionized by the UV background from QSOs if the density is low enough. Consequently, some effort is required to disentangle the photoionized and shock-heated absorbers for purposes of the baryon census. This will likely be challenging, but guidance is already being provided by simulations (Cen et al. 2001; Fang & Bryan 2001).

5. Physical Conditions and Metallicity

As noted in the previous sections, it is important to understand the physical conditions and metallicities of the O VI systems in order to assess their baryonic
content. What fraction of the O VI (and Lyα) absorbers are photoionized? How can the photoionized and collisionally ionized systems be distinguished? Answering these questions will greatly alleviate the double-counting problem. What metallicity should be assumed for calculation of $\Omega_b$(O VI)? Physical conditions and metallicity are interesting properties in their own right, for understanding the nature and evolution of the IGM and its influence on and interaction with galaxies and large-scale structures.

Our group has scrutinized the ionization mechanism in several O VI absorbers and derived metallicity constraints (e.g., Tripp & Savage 2000; Tripp et al. 2001; Savage et al. 2001). It is often difficult to definitely rule out one source of ionization or another, but in several cases one ionization mechanism is strongly favored. For example, in the intervening O VI absorber at $z_{\text{abs}} = 0.06807$ in the spectrum of PG0953+415, H I, C III, C IV, and N V lines are detected and are
well-aligned with the O VI lines, and all of the column densities are reproduced by a photoionization model with metallicity $Z = 0.4_{-0.2}^{+0.6}Z_{\odot}$ (Savage et al. 2001). Perhaps more importantly, the H I Lyα and Lyβ lines associated with the O VI are narrow and appear to be composed of only one component, and the upper limit on $T$ from the width of the H I lines is $T \leq 4.1 \times 10^4$ K. This precludes collisional ionization, at least in equilibrium, unless the H I arises in a different phase from the O VI. A similar situation is found for the O VI system studied by Tripp & Savage (2000), although in this case it is possible to hide a broad component in the complicated Lyα profile, assuming the absorber is a multiphase medium (see their Figure 6). The O VI/Lyα system at $z_{\text{abs}} = 0.1212$ in the spectrum of H1821+643 is an example of a system which is likely collisionally ionized (Tripp et al. 2001). In this case a very broad component is evident in the Lyα profile, which implies that the gas has $T \leq 10^{5.6}$ K. In addition, C IV is not significantly detected, and the O VI/C IV column density ratio provides a lower limit on $T$. Assuming the absorber is collisionally ionized and in equilibrium, Tripp et al. derive $10^{5.3} \leq T \leq 10^{5.6}$ K and $-1.8 \leq [\text{O/H}] \leq -0.6$.

The $b$–values of the lines provide an important clue regarding the physical conditions of the absorbers. They provide a straightforward upper limit on the temperature of the gas, $T \leq mb^2/2k$ (an upper limit because other factors besides thermal motions, such as turbulence or unresolved blended components, can contribute to the line width). The Lyα lines provide the most useful constraint along these lines due to the lower mass of hydrogen. However, Fang & Bryan (2001) and Cen et al. (2001) have recently noted that in their cosmological simulations, the photoionized and collisionally ionized O VI systems can be distinguished on the basis of the O VI $b$–values: the photoionized absorbers are narrower and have lower equivalent widths than the collisionally ionized systems. Figure 5 shows the Doppler parameters and column densities of the O VI absorbers in Table 1, determined using the profile-fitting software written by Fitzpatrick & Spitzer (1997) with the line-spread functions from the STIS Handbook, along with the formal $1\sigma$ error bars from the profile-fitting code. The Doppler parameter of an O VI line arising in gas at $T = 300,000$ K, assuming the line width is dominated by thermal broadening, is shown with a dashed line. The median $b$–value of the entire sample is 22 km s$^{-1}$, and the median O VI column density is $8.7 \times 10^{13}$ cm$^{-2}$. Of course, some of the “single-component” systems are so broad that we can be confident that the broadening is not entirely due to thermal motions (e.g., the highest column density system in the figure), but we do not have sufficient information in the line profiles to decompose these cases into subcomponents. Nevertheless, it is intriguing that the majority of the lines shown in Figure 5 have $b$–values reasonably close to the value expected for gas at $T \sim 300,000$ K, the temperature at which O VI peaks in abundance. There are a few apparently narrow O VI lines (but usually these are consistent with $T \sim 300,000$ K within the $1\sigma$ error bars), and these tend to be weaker.

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2It is alternatively possible, if the density is high enough, that the gas was initially hot enough to be collisionally ionized but then cooled more rapidly than it recombined leading to overionized, cool gas (see, e.g., Edgar & Chevalier 1986).

3$[\text{O/H}] = \log (\text{O/H}) - \log (\text{O/H})_{\odot}$. 
systems. This suggests that most of the O VI absorbers arise in collisionally ionized hot gas.

6. Summary

This contribution has briefly summarized results obtained from high-resolution spectroscopy of low-redshift O VI absorbers. Initial observations indicate that there is a high number of O VI systems per unit redshift in the nearby universe, and these systems likely harbor a significant quantity of baryons. More observations are planned to increase the sample size and total redshift path and thereby place these measurements on firmer statistical grounds. The systems are correlated with luminous galaxies and are intervening, not ejected/intrinsic absorbers. However, the nature of the relationship between galaxies and O VI systems is not yet clear – these lines could arise in unvirialized large-scale filaments (Cen et al. 2001), the intragroup medium in galaxy groups (Mulchaey et al. 1996), escaping winds from individual galaxies (Heckman et al. 2001), or the bound ISM of individual galaxies (Jenkins 1978; Savage et al. 2000). The physical conditions and metallicities show a broad range of properties, but in some cases the absorbing media are multiphase. In general, the properties of the O VI absorbers appear to be broadly consistent with predictions of cosmological simulations of structure growth, but much more observational work and improvements in the simulations are required to flesh out the nature of these absorption line systems and accurately assess their contribution to the baryon budget.

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