

THE SURPRISINGLY CONSTANT STRENGTH OF O VI ABSORBERS OVER COSMIC TIME

ANDREW J. FOX

European Southern Observatory, Alonso de Córdova 3107, Casilla 19001, Vitacura, Santiago, Chile; afox@eso.org
 Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, UK

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ABSTRACT

O VI absorption is observed in a wide range of astrophysical environments, including the local interstellar medium, the disk and halo of the Milky Way, high-velocity clouds, the Magellanic Clouds, starburst galaxies, the intergalactic medium (IGM), damped Ly α systems, and gamma-ray-burst host galaxies. Here, a new compilation of 775 O VI absorbers drawn from the literature is presented, all observed at high resolution (instrumental FWHM ≤ 20 km s $^{-1}$) and covering the redshift range $z = 0$ –3. In galactic environments [$\log N(\text{H I}) \gtrsim 20$], the mean O VI column density is shown to be insensitive to metallicity, taking a value $\log N(\text{O VI}) \approx 14.5$ for galaxies covering the range $-1.6 \lesssim [\text{O}/\text{H}] \lesssim 0$. In intergalactic environments [$\log N(\text{H I}) < 17$], the mean O VI component column density measured in data sets of similar sensitivity shows only weak evolution between $z = 0.2$ and $z = 2.3$, but IGM O VI components are on average almost twice as broad at $z = 0.2$ than at $z = 2.3$. The implications of these results on the origin of O VI are discussed. The existence of a characteristic value of $\log N(\text{O VI})$ for galactic O VI absorbers, and the lack of evolution in $\log N(\text{O VI})$ for intergalactic absorbers, lend support to the “cooling-flow” model of Heckman et al., in which all O VI absorbers are created in regions of initially hot shock-heated plasma that are radiatively cooling through coronal temperatures. These regions could take several forms, including conductive, turbulent, or shocked boundary layers between warm ($\sim 10^4$ K) clouds and hot ($\sim 10^6$ K) plasma, although many such layers would have to be intersected by a typical galaxy–halo sight line to build up the characteristic galactic $N(\text{O VI})$. The alternative, widely used model of single-phase photoionization for intergalactic O VI is ruled out by kinematic evidence in the majority of IGM O VI components at low and high redshift.

Key words: cosmology: observations – galaxies: evolution – galaxies: ISM – intergalactic medium – quasars: absorption lines

Online-only material: color figures

1. INTRODUCTION

In a ground-breaking paper discussing the theoretical basis for a hot Galactic corona, Spitzer (1956) correctly predicted that the lithium-like O $^{+5}$ ion “might be sufficiently abundant to produce measurable absorption” in the UV spectra of background sources, and could therefore be used to detect and analyze such a corona. O VI absorption in its far-ultraviolet resonance doublet at 1031.926 and 1037.617 Å is now routinely detected in the interstellar medium (ISM) of the Milky Way, the extended halos of other galaxies, and the intergalactic medium (IGM) from $z = 0$ to ≈ 3 . The high cosmic abundance of oxygen, the intrinsic strength of the O VI doublet, and the ability to probe warm/hot gas all combine to make O VI a powerful and well-studied tracer of the diffuse universe.

It is common practice to study the detailed properties of O VI absorption in a specific interstellar or intergalactic location. An alternative, global approach is to compare O VI measurements from many different locations, and search for correlations with other observable parameters (such as redshift and metallicity). Along these lines, Heckman et al. (2002, hereafter H02) synthesized O VI observations across several low-redshift environments, and proposed a unified model in which all O VI absorbers (both galactic and intergalactic) trace radiatively cooling regions of initially hot gas. In the last eight years, many new high-resolution (instrumental FWHM ≤ 20 km s $^{-1}$) O VI data sets have become available. In order to draw them together, and to gain insight into the nature of O VI absorbers, a new, heterogeneous compilation of 775 O VI absorbers is presented in this paper. The compilation includes galactic O VI covering galaxy metallicities in the range ≈ 0.01 –1 times solar, and intergalactic

O VI covering redshifts from $z = 0$ to $z \approx 2.5$. In Section 2, the relevant O VI ionization physics is briefly reviewed. In Section 3, a survey of all published interstellar and intergalactic O VI absorbers is presented. The new galactic and intergalactic compilations are presented in Sections 4 and 5, respectively, together with a discussion of their properties. The key results are summarized in Section 6.

2. BRIEF OVERVIEW OF O VI IONIZATION PHYSICS

The energy required to ionize O $^{+4}$ to O $^{+5}$ (the ion traced by O VI) is 113.9 eV (8.4 Rydbergs), whereas ionizing O $^{+5}$ to O $^{+6}$ requires 138.1 eV (10.2 Rydbergs). In a given plasma, the O VI ionization fraction $f(\text{O VI}) \equiv \text{O VI}/\text{O}$ will be set by the balance between ionization from lower states and recombination from higher states. The ionization process can be either ion–electron collisions in high-temperature plasma (collisional ionization) or photoionization by extreme-UV radiation. Collisional ionization of O VI requires “coronal” plasma temperatures of $\sim 10^5$ – 10^6 K, with the ion fraction $f(\text{O VI})$ reaching a maximum of ≈ 0.22 near 300,000 K (Sutherland & Dopita 1993; Bryans et al. 2006; Gnat & Sternberg 2007) in the case of collisional ionization equilibrium (CIE). However, non-equilibrium conditions are likely given that the interstellar cooling function peaks at coronal temperatures, and that coronal plasma is thermally unstable (Kafatos 1973; Shapiro & Moore 1976; Edgar & Chevalier 1986; Wiersma et al. 2009). Under non-equilibrium conditions, the cooling time can be shorter than the recombination time, resulting in “frozen-in” O VI persisting to lower temperatures than would hold under CIE. This has the important consequence that narrow O VI components are not necessarily

photoionized; they can also trace cooled, initially hot plasma. Given the additional complication of non-thermal broadening, O VI line widths (b -values) by themselves do not offer a clean discriminator between ionization mechanisms. Photoionization of O VI is possible if the density of EUV photons with $E > 113.9$ eV is high enough, e.g., near active galactic nuclei (AGNs) and gamma-ray bursts (GRBs). In the Galactic ISM (and by extension, in the ISM of external galaxies), the ionizing radiation field has a sharp break at 54 eV caused by the He II edge in hot-star spectra (Bregman & Harrington 1986), and so photoionization is ruled out as the origin of the observed O VI absorption. In the IGM, photoionization models (Hamann 1997; Bergeron et al. 2002; Lehner et al. 2006; Howk et al. 2009) indicate that the production of O VI by the extragalactic background (EGB) radiation requires an ionization parameter $U \equiv n_\gamma/n_H$ (the ratio of the ionizing photon density to the gas density) in the range ≈ 0.1 – 1 at any redshift, so long as the shape of the EGB does not change substantially, which is reasonable for the redshift range $z = 0$ – 3 over which O VI can be observed (Haardt & Madau 1996, 2001).

3. PUBLISHED O VI ABSORPTION DETECTIONS

In this paper, *galactic* (interstellar) and *intergalactic* O VI absorbers are distinguished by a simple cut made in H I column density, referring to absorbers with $N(\text{H I}) > 10^{17} \text{ cm}^{-2}$ and $N(\text{H I}) < 10^{17} \text{ cm}^{-2}$, respectively. This approach is powerful since the H I lines can often be measured in the same spectra as the O VI lines. Of course, the galactic/intergalactic division is not clear-cut and somewhat arbitrary; Wakker & Savage (2009) report that *all* low- z O VI absorbers arise within 550 kpc of an $L > 0.25L_\star$ galaxy, so all O VI absorbers could be called galactic at some level (see also Stocke et al. 2006). Nonetheless, the distinction at 10^{17} cm^{-2} is still useful: it represents the transition where an absorber becomes optically thick to hydrogen-ionizing radiation at $\lambda < 912 \text{ \AA}$. The distinction also fits historically defined observational categories: intergalactic absorbers are traced by the Ly α forest, whereas galactic absorbers can be divided into Lyman limit systems (LLSs) with $17 < \log N(\text{H I}) < 19$, sub-damped Ly α systems (sub-DLAs or super LLSs) with $19 < \log N(\text{H I}) < 20.3$, and genuine damped Ly α systems (DLAs) with $\log N(\text{H I}) > 20.3$, which represent structures of progressively higher overdensity.

In order to prepare the compilations, a review of all published interstellar and intergalactic O VI absorption detections is now presented. Readers interested in the new results drawn from the compilations may wish to skip to Section 4.

3.1. Galactic (Milky Way) O VI

The first detections of interstellar O VI absorption were made with the *Copernicus* satellite, along sight lines through the Galactic disk (Rogerson et al. 1973; York 1974, 1977; Jenkins & Meloy 1974; Jenkins 1978a, 1978b; Cowie et al. 1979; Shelton & Cox 1994). This revealed a network of highly ionized interstellar clouds seen in the form of low-velocity ($|v_{\text{LSR}}| \lesssim 100 \text{ km s}^{-1}$) O VI absorption components. A small number of O VI detections were made with the Astro-1 (Davidsen 1993) and *Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer (ORFEUS)* Space Shuttle missions (Hurwitz et al. 1998; Widmann et al. 1998; Sembach et al. 1999). The study of interstellar O VI absorption flourished following the launch of the *Far-Ultraviolet Spectroscopic Explorer (FUSE)* satellite in 1999. Many *FUSE* studies of O VI

took the form of surveys over many lines of sight, each targeting different regions of the Galaxy, either the local ISM (LLSM; Oegerle et al. 2000; Savage & Lehner 2006; Welsh & Lallement 2008; Barstow et al. 2010), the Galactic disk (latitudes $|b| < 10^\circ$; Bowen et al. 2008; Lehner et al. 2011), or the Galactic halo ($|b| > 10^\circ$; Savage et al. 2000, 2003; Wakker et al. 2003; Zsargó et al. 2003; Indebetouw & Shull 2004b; Savage & Wakker 2009). Other *FUSE* studies analyzed the O VI absorption in individual disk and halo directions (Richter et al. 2001a; Nicastro et al. 2002; Sterling et al. 2002; Fox et al. 2003; Howk et al. 2003; Welsh et al. 2004; Williams et al. 2005, 2006, 2007; Yao et al. 2009b), and the small-scale structure in O VI using closely spaced (degree-scale) sight lines (Howk et al. 2002a; Lehner & Howk 2004). *Chandra* X-ray observations of zero-redshift (interstellar) absorption in the K-shell line of O VI at 22.040 Å have also been reported (Nicastro et al. 2005; Williams et al. 2005; Yao et al. 2009a).

In addition to these low-velocity detections, O VI is also commonly detected in high-velocity clouds (HVCs), defined as absorption features at $|v_{\text{LSR}}| > 100 \text{ km s}^{-1}$ (and in practice $|v_{\text{LSR}}| \lesssim 400 \text{ km s}^{-1}$) seen in the spectra of background AGN (Sembach et al. 2000, 2002, 2003; Murphy et al. 2000; Richter et al. 2001b; Tripp et al. 2003; Nicastro et al. 2003; Collins et al. 2003, 2004, 2005, 2007; Fox et al. 2004, 2005, 2006; Ganguly et al. 2005; Keeney et al. 2006) or distant halo stars (Zech et al. 2008). HVCs trace a variety of processes in the extended gaseous halo of the Milky Way, including accretion, outflow, and the stripping of gas from nearby satellites. O VI absorption has also been detected in individual Galactic interstellar objects, such as the Cygnus Loop supernova remnant (Blair et al. 2002, 2009) and the Southern Coalsack dark nebula (Andersson et al. 2004).

3.2. O VI in Nearby Galaxies

O VI absorption is detected in the LMC (Friedman et al. 2000; Blair et al. 2000; Howk et al. 2002b; Danforth et al. 2002; Danforth & Blair 2006; Lehner & Howk 2007; Lehner et al. 2009b; Pathak et al. 2010), the Small Magellanic Cloud (SMC; Hoopes et al. 2002; Danforth et al. 2002), and the Magellanic Bridge (Lehner 2002) and Magellanic Stream (Sembach et al. 2003; Fox et al. 2005, 2010), which trace the interactions between the two Magellanic Clouds and the Milky Way. The typical O VI column densities in the LMC (Howk et al. 2002b; Pathak et al. 2010) are comparable to those in the Milky Way halo; those seen in the SMC (Hoopes et al. 2002) are slightly higher. Strong O VI absorption is detected in the starburst galaxy NGC 1705 (Heckman et al. 2001), the merging galaxy VV 114 (Grimes et al. 2006), the UV-luminous galaxy Haro 11 (Grimes et al. 2007), and in 12 of the 16 low-redshift starburst galaxies studied by Grimes et al. (2009).

3.3. Low-redshift ($z \lesssim 0.5$) Intergalactic O VI

The study of low-redshift intergalactic O VI absorption was enabled by the launch of *Hubble Space Telescope (HST)* and the installation of a series of high-resolution ultraviolet spectrographs (GHRS, STIS, and COS). Following the detection of O VI at $z = 0.14232$ toward QSO PG 0953+415 by Tripp et al. (2000), detections and detailed analyses of low-redshift intergalactic O VI absorbers were reported by many groups. Most of these studies focused on individual sight lines (Tripp & Savage 2000; Tripp et al. 2001, 2002, 2006a; Sembach et al.

2001, 2004; Savage et al. 2002, 2005a, 2005b; Williger et al. 2006, 2010; Lehner et al. 2006, 2009a; Narayanan et al. 2010b, 2010c; Oegerle et al. 2005; Jenkins et al. 2003; Shull et al. 2003; Richter et al. 2004; Prochaska et al. 2004; Tumlinson et al. 2005; Cooksey et al. 2008; Howk et al. 2009; Lacki & Charlton 2010; Danforth et al. 2010). Others took the form of surveys of all available data (Danforth & Shull 2005, 2008; Danforth et al. 2006; Tripp et al. 2008; Thom & Chen 2008a, 2008b). Bregman et al. (2004) report three O VI absorption-line detections in sight lines passing through low- z galaxy clusters, arguing that these detections trace intergalactic filaments.

The association between intergalactic O VI absorbers and nearby galaxies has been investigated by searching the fields around bright quasars for nearby galaxies (Stocke et al. 2006; Prochaska et al. 2006; Wakker & Savage 2009; Chen & Mulchaey 2009), and correlating the absorber redshifts with the galaxy redshifts. Wakker & Savage (2009) report that all O VI absorbers arise within 550 kpc of an $L > 0.25L_*$ galaxy, and there is no evidence for O VI in intergalactic voids (Stocke et al. 2006, 2007), defined as absorbers at >1.4 Mpc from the nearest $L > L_*$ galaxy. Other galaxy/O VI relationships have been investigated via the O VI detections (1) at $z = 0.225$ and $z = 0.297$ toward QSO H1821+643 (Savage et al. 1998), close in redshift to two nearby spiral galaxies, (2) in the LLS at $z = 0.16716$ toward QSO PKS 0405–123, thought to be associated with a pair of nearby galaxies (Chen & Prochaska 2000; Savage et al. 2010), and (3) in the halo of a $\approx 2L_*$ spiral galaxy at $z = 0.22$ (Narayanan et al. 2010a).

An important subset of the IGM absorbers are the “proximate” (also called “associated” or “ $z_{\text{abs}} \approx z_{\text{em}}$ ”) absorbers, defined as those within a fixed velocity interval (typically 5000 km s^{-1} , but sometimes 3000 km s^{-1} , 2500 km s^{-1} or 1500 km s^{-1}) of the background QSO (e.g., Foltz et al. 1986; Tripp et al. 2008; Fox et al. 2008a). Such proximate absorbers are usually excluded from intervening samples in order to avoid truly intrinsic absorbers, proximity effects, and environmental effects. Truly intrinsic absorbers, tracing inflowing and outflowing gas arising near the central engines of AGN, represent a separate category of object and lie outside the scope of this paper. Fortunately, they can usually be identified by their saturated high-ion profiles, time variation of absorption, evidence for partial coverage of the continuum source, and/or the presence of excited-state absorption lines (e.g., Hamann & Ferland 1999; Simon & Hamann 2010, and references therein). The remaining (non-intrinsic) proximate absorbers are included in the compilation presented in this paper.

3.4. Intermediate-redshift ($0.5 \lesssim z \lesssim 2.0$) Intergalactic O VI

Intermediate-redshift intergalactic O VI absorption was first detected with the low-resolution *HST*/Faint Object Spectrograph (FOS) by the surveys of Bergeron et al. (1994) and Januzzi et al. (1998). Detailed studies of individual intermediate- z absorbers followed, both with FOS (Churchill & Charlton 1999; Lopez et al. 1999) and STIS/E230M (Reimers et al. 2001, 2006; Levshakov et al. 2002, 2003b; Milutinović et al. 2007). Most of these studies have probed the range $1.0 \lesssim z \lesssim 2.0$; the range $0.5 \lesssim z \lesssim 1.0$ remains largely unobserved in O VI, largely because of the small effective area of near-UV space-based spectrographs, and the shortage of UV-bright AGN at sufficiently high redshift.

3.5. High-redshift ($z \gtrsim 2.0$) Intergalactic O VI

Above $z \approx 2.0$, the O VI doublet becomes detectable from the ground, where it can be measured using high-resolution spectrographs. However, high-redshift O VI detections are complicated by the possibility of blending with intervening Ly α forest absorbers. The rapidly increasing density of the forest with increasing redshift makes O VI absorption detections in individual systems above $z \approx 3$ very challenging, but not impossible (Burles & Tytler 1996; Frank et al. 2010a).

The earliest evidence for the presence of intergalactic O VI absorption at $z \gtrsim 2.0$ came from features seen in composite spectra formed by stacking individual frames (Lu & Savage 1993; Davé et al. 1998). Since then, high- z IGM O VI detections have been reported in many individual systems studied at high resolution (Bergeron et al. 2002; Carswell et al. 2002; Simcoe et al. 2004, 2006; Levshakov et al. 2003a, 2004, 2009; Agafonova et al. 2005, 2007; Lopez et al. 2007; Schaye et al. 2007; Gonçalves et al. 2008; Fechner & Richter 2009), and several high- z O VI surveys exist (Simcoe et al. 2002; Bergeron & Herbert-Fort 2005; Fox et al. 2008a). Furthermore, 1756 O VI doublet candidates (of which 145 fall in the most secure category) have been reported in a Sloan Digital Sky Survey (SDSS) database of 3702 QSOs observed at low resolution (Frank et al. 2010a, 2010b). A complementary, statistical approach for detecting intergalactic O VI is the pixel optical depth method, where one searches pixel-by-pixel for a Ly α signal and measures whether absorption appears at the corresponding O VI pixel (Schaye et al. 2000; Aracil et al. 2004; Pieri & Haehnelt 2004; Pieri et al. 2006, 2010; Aguirre et al. 2008). This method is increasingly being used on large samples of low-resolution spectra, and allows O VI to be detected out to $z > 3$ (Pieri et al. 2010).

3.6. High-redshift ($z \gtrsim 2.0$) Galactic O VI

O VI detections have been reported in each of the three classes of optically thick (galactic) quasar absorption-line system at $z \gtrsim 2.0$: in LLSs (Kirkman & Tytler 1997, 1999; D’Odorico & Petitjean 2001), in sub-DLAs (Simcoe et al. 2002; Fox et al. 2007b), and in DLAs (Fox et al. 2007a; Lehner et al. 2008; Ellison et al. 2010). A composite spectrum of 341 DLAs in the SDSS database shows clear O VI absorption (Rahmani et al. 2010). O VI has also been detected in the host galaxies of high-redshift GRBs (D’Elia et al. 2007, 2010; Fox et al. 2008b), which can be viewed as a subset of DLAs, known as GRB-DLAs, though in these cases there may be a contribution to the O VI from the circumburst region immediately surrounding the GRB (Prochaska et al. 2008).

4. COMPILATION OF GALACTIC O VI

In Figure 1, the new compilation of galactic O VI absorbers is presented. It includes a total of 447 O VI measurements made at high resolution, covering 24 LISM sight lines (Savage & Lehner 2006), 131 Galactic disk sight lines (Bowen et al. 2008), 91 Galactic halo sight lines (Savage et al. 2003), 84 HVCs (Sembach et al. 2003), 18 SMC sight lines (Hoopes et al. 2002), 70 LMC sight lines (Pathak et al. 2010), 12 starburst galaxies with O VI detections (Grimes et al. 2009), 12 DLAs at $z = 2-3$ (Fox et al. 2007a), and five GRB-DLAs at $z = 2-4$ (Fox et al. 2008b). All these environments have $\log N(\text{H I}) \gtrsim 17$, and most have $\log N(\text{H I}) \gtrsim 20$. The galactic compilation is summarized in Table 1, with details of each set of measurements given in the footnotes. All O VI measurements (except for the Galactic disk, where profile fitting was used) were

Table 1
Compilation of Galactic O VI Absorbers [$\log N(\text{H I}) > 17$]

Location	Number ^a	$\langle z \rangle$	$\langle [\text{O}/\text{H}] \rangle^b$	$\langle \log N(\text{O VI}) \rangle^c$	Instrument	Reference
<i>Local ISM</i> ^d	24	0	...	13.09 ± 0.30	<i>FUSE</i>	Savage & Lehner (2006)
Galactic disk ($ b < 10^\circ$) ^e	131	0	~ 0.0	14.15 ± 0.35	<i>FUSE</i>	Bowen et al. (2008)
Galactic halo ($ b > 10^\circ$) ^f	91	0	~ -0.25	14.36 ± 0.18	<i>FUSE</i>	Savage et al. (2003)
<i>High-velocity clouds (HVCs)</i> ^g	84	0	~ -0.25	13.95 ± 0.34	<i>FUSE</i>	Sembach et al. (2003)
SMC ^h	18	0.00053	-0.66 ± 0.10	14.58 ± 0.17	<i>FUSE</i>	Hoopes et al. (2002)
LMC ⁱ	70	0.00094	-0.34 ± 0.06	14.24 ± 0.19	<i>FUSE</i>	Pathak et al. (2010)
Starburst galaxies ^j	12	0.0128	-0.36 ± 0.47	14.92 ± 0.34	<i>FUSE</i>	Grimes et al. (2009)
DLAs ^k	12	2.56	-1.62 ± 0.61	14.47 ± 0.54	UVES	Fox et al. (2007a)
... high metallicity ($[\text{Z}/\text{H}] > -1.63$)	(6)	2.46	-1.18 ± 0.50	14.79 ± 0.49	UVES	Fox et al. (2007a)
... low metallicity ($[\text{Z}/\text{H}] < -1.63$)	(6)	2.65	-2.06 ± 0.34	14.16 ± 0.42	UVES	Fox et al. (2007a)
GRB host galaxies ^l	5	2.72	...	$> 14.81 \pm 0.22$	UVES	Fox et al. (2008b)

Notes. Entries in italics denote partial (rather than extended) galaxy–halo sight lines.

^a Number of sight lines in sample, except for HVCs, where the number of individual components is given. The numbers of sub-samples are given in parentheses.

^b Mean gas-phase metallicity (logarithmic scale relative to solar).

^c Mean and standard deviation of logarithmic O VI column density in cm^{-2} .

^d LISM results given here are for O VI detections only; 15 non-detections and seven cases with possible stellar contamination are ignored. Columns measured along short (≈ 40 – 200 pc) sight lines.

^e Galactic disk results given here are for O VI detections only and are derived from Voigt-profile fits; 17 non-detections are ignored. Solar metallicity is assumed.

^f Galactic halo columns integrated over $-100 < v_{\text{LSR}} < 100 \text{ km s}^{-1}$. Results given here are for O VI detections only; 11 non-detections are ignored. ≈ 0.5 solar metallicity is assumed.

^g HVCs are individual clouds with $|v_{\text{LSR}}| > 100 \text{ km s}^{-1}$. Eighty-four HVCs were measured along 100 sight lines. ≈ 0.5 solar metallicity is assumed.

^h SMC columns integrated over $v_{\text{LSR}} \approx 50$ – 260 km s^{-1} . $[\text{O}/\text{H}]_{\text{SMC}}$ from Russell & Dopita (1992).

ⁱ LMC columns integrated over $v_{\text{LSR}} \approx 160$ – 360 km s^{-1} . $[\text{O}/\text{H}]_{\text{LMC}}$ from Russell & Dopita (1992).

^j Starburst O VI columns integrated over full velocity ranges observed, typically ≈ 200 – 300 km s^{-1} ; four non-detections are ignored. Metallicities derived from nebular emission lines.

^k DLA results are for 12 DLAs with O VI detections; 23 cases with blended O VI are ignored. DLA metallicities shown are $[\text{Z}/\text{H}]$, where $\text{Z} = \text{Zn}, \text{S}, \text{or Si}$.

^l GRB host galaxy O VI columns integrated over full velocity ranges observed, typically $\approx 200 \text{ km s}^{-1}$ around the burst redshift. All individual GRB O VI columns are lower limits (due to saturation), so the mean is also a lower limit. GRB host galaxy metallicities are not well characterized and are not shown.

made using the apparent optical depth (AOD) method (Savage & Sembach 1991), integrating over the observed range of absorption, and were retrieved from tables in the online versions of the papers cited (except the GRB-DLA AOD measurements, which were remade by the author). The AOD method gives accurate measurements of the true column density unless the lines are saturated, in which case the results are lower limits. Saturation is present for all O VI absorbers in the GRB-DLA sample, and for several objects in the starburst galaxy sample.

On the left side of Figure 1 are the LISM O VI measurements, made along short (~ 40 – 200 pc) sight lines with a well-known geometry (Savage & Lehner 2006). The O VI in the LISM is thought to arise at the interface between the Local Bubble, the cavity of hot ($\sim 10^6$ K) gas immediately surrounding the Sun, and the neutral gas beyond (Savage & Lehner 2006; Barstow et al. 2010). This is supported by the observation that the typical O VI column density measured along LISM sight lines is close to the value predicted theoretically in a single conductive interface, $N(\text{O VI}) \approx 10^{13} \text{ cm}^{-2}$ (Borkowski et al. 1990; Gnat et al. 2010). The LISM column densities cannot be easily compared to those measured in extended sight lines through other galactic halos, which cover length scales on the order of kpc to tens of kpc. All the extended sight-line samples shown in Figure 1 (i.e., all samples except the LISM and HVCs) have mean O VI columns confined to a narrow range between $\log N(\text{O VI}) = 14.1$ and 14.9 (the Galactic disk sight lines studied by Bowen et al. (2008) have lengths of ≈ 0.8 – 10 kpc, and are therefore treated here as extended).

To emphasize the relatively small range in O VI column shown by these diverse galaxies, in Figure 2 the mean $\log N(\text{O VI})$ is plotted versus gas-phase metallicity for the extended sight-

line samples. Here, the mean O VI column densities through the Milky Way and HVCs have been summed to determine the total O VI column in a (one-sided) sight line through the Milky Way halo (integrated over velocity), allowing a better comparison with the other galactic environments. The main finding of Figure 2 is that the mean column density for galactic O VI is surprisingly constant over two orders of magnitude of metallicity, with the Galactic disk, the Galactic halo, the LMC, the SMC, starburst galaxies, and DLAs at $z = 2$ – 3 all showing $\langle \log N(\text{O VI}) \rangle$ within 0.4 dex of 14.5. The existence of a characteristic $\log N(\text{O VI})$ in galactic environments has been noticed before (H02, Savage et al. 2003). What is new here is the observational finding that the insensitivity of $N(\text{O VI})$ to galaxy metallicity extends down to $-1.6 \lesssim [\text{O}/\text{H}] \lesssim -0.6$, to the upper end of the DLA metallicity regime. Below -1.6 , $\langle \log N(\text{O VI}) \rangle$ falls off and is no longer independent of metallicity: the low-metallicity sub-sample of DLAs shows a mean $\log N(\text{O VI})$ 0.5 dex lower than the high-metallicity sub-sample (Fox et al. 2007a). If one reduces the mean DLA O VI column by a factor of two (0.3 dex) to correct for the two-sided nature of a DLA–halo sight line (as opposed to the Milky Way, LMC, SMC, and starburst galaxy cases, where the sight line only passes through one side of the halo), then the constancy of O VI (down to $[\text{O}/\text{H}] \approx -1.5$) becomes even more striking.

The non-dependence of $N(\text{O VI})$ on metallicity has an important consequence on the total ionized hydrogen column in the O VI absorbers $N(\text{H II})_{\text{O VI}}$, which can be written as $N(\text{H II})_{\text{O VI}} = N(\text{O VI})/[(\text{O}/\text{H})f(\text{O VI})]$, and so scales inversely with metallicity. If the ionization fraction $f(\text{O VI})$ is treated as a constant (as is possible if a common origin mechanism applies), then the constant value of $N(\text{O VI})$ implies that the

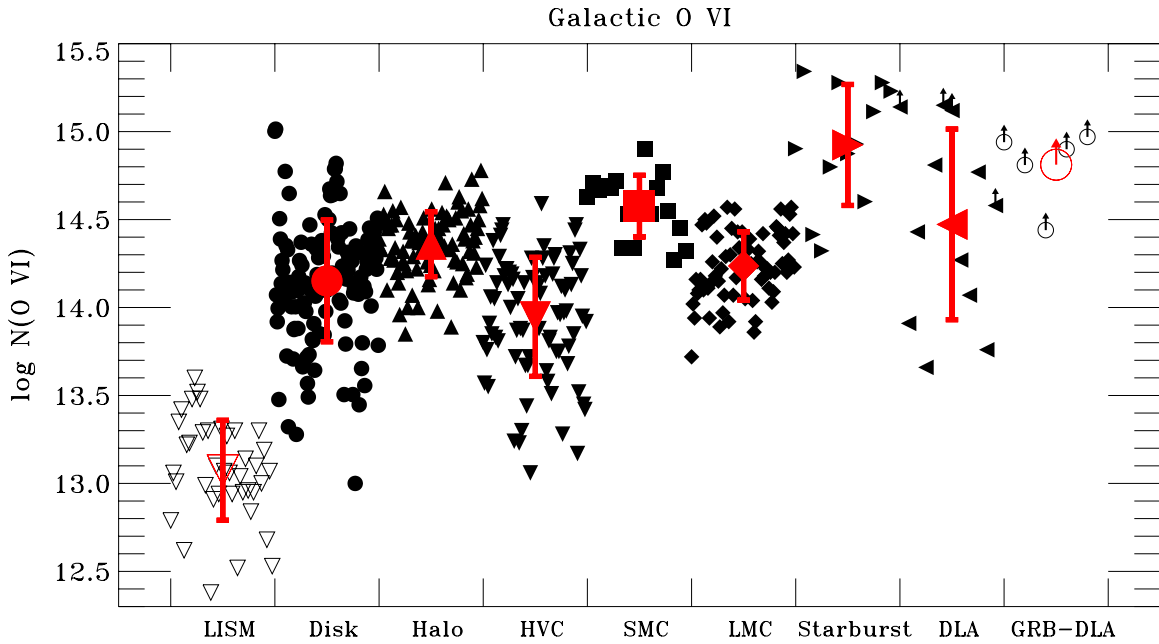


Figure 1. Comparison of O VI column density in various *galactic* environments, derived from apparent optical depth measurements unless noted otherwise. The following samples are shown, ordered by increasing distance: local ISM (Savage & Lehner 2006), Galactic disk (Bowen et al. 2008, profile-fit measurements), Galactic halo (Savage et al. 2003), HVCs (Sembach et al. 2003), the SMC (Hoopes et al. 2002), the LMC (Pathak et al. 2010), starburst galaxies (Grimes et al. 2009), DLAs at $z = 2-3$ (Fox et al. 2007a), and GRB-DLAs (GRB host galaxies) at $z = 2-4$ (Fox et al. 2008b), with a different symbol used for each sample. Within each bin, the data points are spread in the x -direction for clarity. Red symbols with error bars show the mean and standard deviation of $\log N(\text{O VI})$ in each category. For details of each sample see Table 1. Note that the LISM and HVC measurements are made over partial (rather than extended) galaxy-halo sight lines.

(A color version of this figure is available in the online journal.)

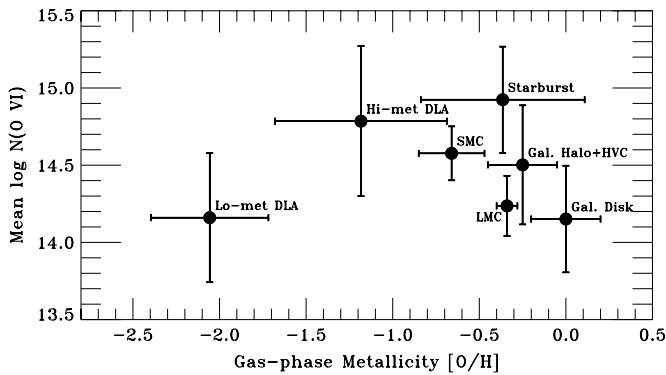


Figure 2. Mean O VI column density vs. gas-phase metallicity for seven samples of galactic O VI absorbers: the Galactic disk (Bowen et al. 2008), Galactic halo plus HVCs (Savage et al. 2003; Sembach et al. 2003), the SMC (Hoopes et al. 2002), the LMC (Pathak et al. 2010), starburst galaxies (Grimes et al. 2009), and DLAs at $z = 2-3$ split into low-metallicity and high-metallicity sub-samples (Fox et al. 2007a). Considering the range of metallicities (and masses) probed, $\langle N(\text{O VI}) \rangle$ is surprisingly insensitive to metallicity.

lower-metallicity galaxies contain *larger* columns of ionized hydrogen at O VI-bearing temperatures. For example, a typical sight line through a high-metallicity DLA, with $\langle N(\text{O VI}) \rangle = 14.79$ and $\langle [\text{O}/\text{H}] \rangle = -1.2$, contains an average $N(\text{H II})_{\text{O VI}}$, a factor of ≈ 17 higher than a typical sight line through the Milky Way halo, which has $\langle N(\text{O VI}) \rangle = 14.50$, and an assumed $\langle [\text{O}/\text{H}] \rangle \approx -0.25$.

4.1. Discussion on Origin of Galactic O VI

Detailed studies of the high ions in the Milky Way (the galaxy with the best-studied gaseous halo) have emphasized that the Galactic halo is a complex environment, with many astrophysical processes potentially at work (Savage et al. 2003;

Indebetouw & Shull 2004b; Bowen et al. 2008), and there is no obvious reason for other galactic halos to be any simpler. Therefore, the existence of a characteristic value for galactic $N(\text{O VI})$ is somewhat surprising, and models that can explain it deserve attention. Such a model was suggested by H02, who argued that the insensitivity of $N(\text{O VI})$ to metallicity could be explained if the O VI arises in radiatively cooling regions of initially hot shock-heated plasma that are passing through the coronal regime (see also Furlanetto et al. 2005). In such a “cooling flow,” $N(\text{O VI}) = 3kT v_{\text{cool}}(\text{O}/\text{H})_{\odot} Z f(\text{O VI})/\Lambda$, where v_{cool} is the cooling-flow velocity and Λ is the cooling function (H02). Since Λ is almost linearly proportional to Z , the Z terms cancel out, elegantly explaining the independence of $N(\text{O VI})$ to metallicity. For $T = 3 \times 10^5$ K (where O VI peaks in CIE) and $f(\text{O VI}) = 0.22$, the equation evaluates to $N(\text{O VI}) = 3 \times 10^{14} (v_{\text{cool}}/100 \text{ km s}^{-1})$, implying a single cooling flow could explain the observed galactic column of $\langle \log N(\text{O VI}) \rangle = 14.5$ if $v_{\text{cool}} \approx 100 \text{ km s}^{-1}$. However, the kinematic complexity of galaxy halos makes such single-zone solutions unlikely. More plausibly, the characteristic value could be explained by a multi-zone cooling-flow scenario, where each galactic sight line intersects a number of cooling regions. If each region contributes an O VI column of $\approx 10^{13} \text{ cm}^{-2}$, the amount seen in the nearby LISM directions (Savage & Lehner 2006; Barstow et al. 2010) and predicted by conductive interface models (Borkowski et al. 1990; Gnat et al. 2010), then ≈ 30 regions are required along the kpc to tens of kpc scale sight lines through galactic halos to build up the characteristic column. In this multi-zone explanation, the constancy of $N(\text{O VI})$ would be due not only to a similar O VI column per interface, but also to a similar number of interfaces intersected by each sight line.

The framework of the H02 model allows the cooling flows to take several forms, including turbulent (Begelman & Fabian

Table 2
Compilation of Intergalactic O VI components [$\log N(\text{H I}) < 17$]

Sample	Number ^a	$\langle z \rangle$	$\langle \log N(\text{O VI}) \rangle^b$	$\langle b(\text{O VI}) \rangle^c$	Instrument	Reference
Low- z intervening	77	0.21	13.78 ± 0.36	26.2 ± 14.2	STIS	Tripp et al. (2008)
... $\log N > 13.2$ only	(73)	0.21	13.82 ± 0.33	26.8 ± 14.2	STIS	"
Low- z proximate	34	0.30	13.80 ± 0.41	19.4 ± 11.0	STIS	"
... $\log N > 13.2$ only	(32)	0.30	13.85 ± 0.37	19.9 ± 11.1	STIS	"
Intermediate- z intervening ^d	18	1.54	13.78 ± 0.35	15.2 ± 3.4	STIS	Reimers et al. (2001, 2006)
Intermediate- z proximate ^d	5	1.77	13.78 ± 0.37	16.8 ± 5.1	STIS	"
High- z intervening	146	2.27	13.56 ± 0.37	14.4 ± 6.9	UVES	Bergeron & Herbert-Fort (2005)
... $\log N > 13.2$ only	(125)	2.28	13.65 ± 0.31	15.1 ± 7.1	UVES	"
High- z proximate	48	2.36	13.45 ± 0.36	14.8 ± 7.8	UVES	Fox et al. (2008a)
... $\log N > 13.2$ only	(33)	2.35	13.64 ± 0.26	17.2 ± 8.2	UVES	"

Notes. “Intervening” and “proximate” refer here to components with velocity offsets from the background QSO of >5000 and <5000 km s⁻¹, respectively. Quasar-intrinsic absorbers are excluded.

^a Sample size: the number of components. Numbers for sub-samples given in parentheses.

^b Mean and standard deviation of logarithmic O VI column density in cm⁻².

^c Mean and standard deviation of O VI b -value in km s⁻¹.

^d All intermediate- z absorbers have $\log N > 13.2$, so no sub-sample is needed.

1990; Slavin et al. 1993; Esquivel et al. 2006; Kwak & Shelton 2010), conductive (Cowie et al. 1979; Böhringer & Hartquist 1987; Borkowski et al. 1990; Gnat et al. 2010), or shocked (Dopita & Sutherland 1996; Indebetouw & Shull 2004a; Gnat & Sternberg 2009) interfaces between warm ($\sim 10^4$ K) interstellar/intergalactic clouds and surrounding hot ($\sim 10^6$ K) plasma. Comparing the detailed predictions of these models to the O VI observations is beyond the scope of this paper, but there are evidently many theoretical reasons to expect radiatively cooling boundary layers to exist in the ISM and IGM.

H02 argued that the cooling-flow model is supported by the O VI $\log N$ - b relation (see also Lehner et al. 2006; Danforth et al. 2006; Tripp et al. 2008; Grimes et al. 2009). That relation is not presented here for the new compilation of O VI absorbers, for two reasons. First, it is difficult to ensure consistency and accuracy when comparing measurements of O VI b -values, because they are (1) measured differently by different groups, (2) difficult to measure in Galactic environments where the O VI lines are often saturated, and (3) not necessarily resolved in spectra of ≈ 20 km s⁻¹ resolution, as is the case with *FUSE*. Second, it is unclear why v_{cool} should be associated with b or with the non-thermal broadening parameter b_{nt} , an implicit assumption when using the $\log N$ - b relation to test the cooling-flow hypothesis. Instead, here it is proposed that v_{cool} could be identified with the velocity-centroid offset δv_0 between O VI and H I (or between O VI and a low-ion line such as C II), because for a given absorber, δv_0 represents a direct measurement of the relative motion along the line of sight between the O VI-bearing and the low-ion plasma phases. Formally, δv_0 gives a lower limit on the absolute value of v_{cool} , since it only measures the line-of-sight component. Unfortunately, measurements of δv_0 are not readily available for the samples shown in Figures 1 and 2, but a search for a $N(\text{O VI})$ - δv_0 relation could form a future test of the cooling-flow model.

5. COMPILATION OF INTERGALACTIC O VI

In Figure 3, the new compilation of intergalactic O VI absorbers is presented. It contains 328 individual O VI components (often grouped into systems) measured with line-profile fitting, and was formed by combining the low- z sample of Tripp et al. (2008, hereafter T08), the intermediate- z samples of Reimers et al. (2001, 2006, hereafter R01 and R06), and the high- z sam-

ples of Bergeron & Herbert-Fort (2005, hereafter BH05) and Fox et al. (2008a, hereafter F08). The low- z sample consists of 77 intervening and 34 proximate components at a mean redshift $\langle z \rangle = 0.23$, measured at ≈ 7 km s⁻¹ resolution with *HST*/STIS/E140M (T08) and a limiting column density (sensitivity) $\log N_{\text{lim}} \approx 13.0$. The intermediate- z sample consists of 18 intervening and five proximate components at $\langle z \rangle = 1.59$, measured at ≈ 10 km s⁻¹ resolution and $\log N_{\text{lim}} \approx 13.2$ sensitivity with *HST*/STIS/E230M (R01, R06). The high- z sample consists of 146 intervening components at $\langle z \rangle = 2.27$ (BH05), and 48 proximate components at $\langle z \rangle = 2.36$ (F08), all measured at 6.6 km s⁻¹ resolution and $\log N_{\text{lim}} \approx 12.8$ sensitivity with Very Large Telescope/UVES. All measurements were taken directly from the online version of the papers cited (except the BH05 measurements, provided by J. Bergeron). The intergalactic compilation is summarized in Table 2.

Two interesting conclusions can be drawn from Figure 3. First, although there is significant scatter at all redshifts, the mean column density of intergalactic O VI components evolves only weakly over cosmic time. Second, at both low and high redshifts, there is no difference in the mean O VI component column density between the intervening and proximate samples. These related results are now discussed at length.

For intervening (non-proximate) O VI components, the mean and standard deviation of $\log N(\text{O VI})$ for components above a limiting $\log N(\text{O VI}) = 13.2$ changes from 13.65 ± 0.31 at $\langle z \rangle = 2.28$ (BH05) to 13.78 ± 0.35 at $\langle z \rangle = 1.54$ (R01, R06), and 13.82 ± 0.33 at $\langle z \rangle = 0.21$ (T08), where the cutoff at 13.2 (corresponding to a limiting rest-frame equivalent width of 20 mÅ) was used to correct for the small difference in sensitivity between the samples. That amounts to a weak evolution in the mean $\log N(\text{O VI})$ of only 0.17 dex (a factor of 1.5) over 8.2 Gyr of cosmic time between $\langle z \rangle = 2.28$ and $\langle z \rangle = 0.21$ (using the online cosmology calculator of Wright 2006). This evolution is weak considering that cosmological simulations predict a globally averaged metallicity that increases from ≈ 0.01 solar at $z = 3$ to ≈ 0.2 solar at $z = 0$ (Cen & Ostriker 1999), i.e., by a factor of ≈ 20 (although the local metallicity is highly dependent on overdensity). Using the median rather than the mean $\log N(\text{O VI})$ does not significantly change any of these results. Kendall rank correlation tests were used to investigate whether $\log N(\text{O VI})$ and z are statistically related. A

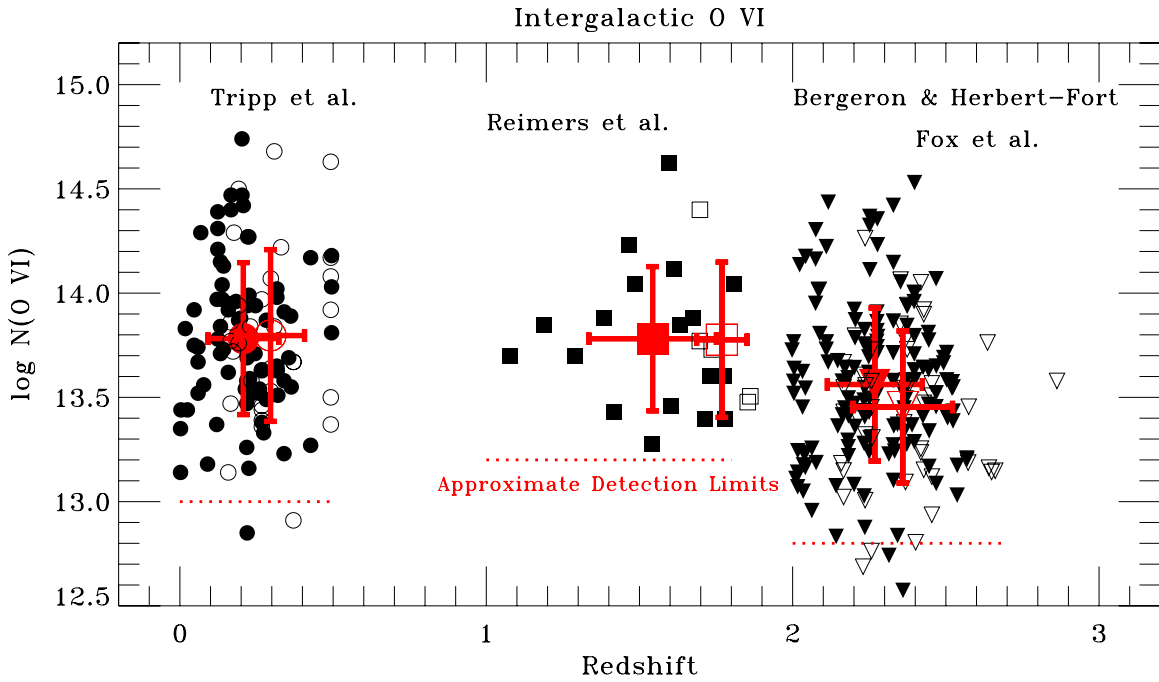


Figure 3. Column density in intergalactic O VI components as a function of redshift, using results from line-profile fitting. Shown are low- z data from T08, intermediate- z data from R01 and R06, and high- z data from BH05 and F08. Proximate absorbers (within 5000 km s^{-1} of the QSO redshift) are shown with open symbols. Red symbols with error bars show the mean and standard deviation of $\log N(\text{O VI})$ and z in each sample. Approximate detection limits for each sample are shown with red dotted lines.

(A color version of this figure is available in the online journal.)

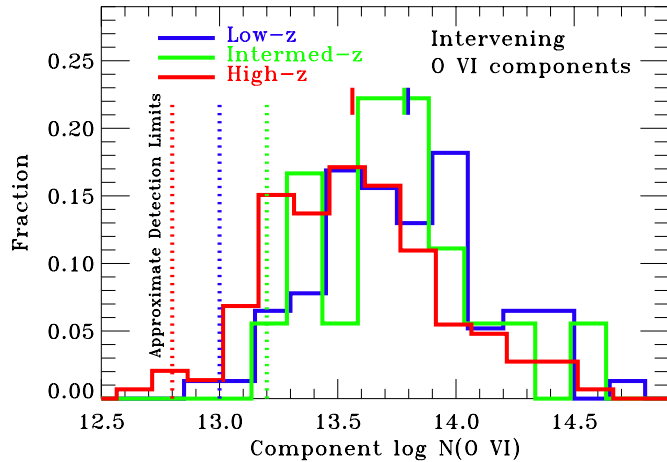


Figure 4. Distribution of column density in intervening O VI components at low- z (T08), intermediate- z (R01, R06), and high- z (BH05) using a bin size of 0.15 dex. The mean value of each distribution is shown with a color-coded tick mark. Dotted lines show the approximate detection limit of each sample.

(A color version of this figure is available in the online journal.)

correlation coefficient of -0.17 was found at high significance, indicating that the evolution in $\log N$ is weak but real. The same correlation coefficient (-0.17) was found when using the entire (intervening+proximate) sample. The weak evolution in the mean O VI column density is highlighted in Figure 4, which compares the distribution of $\log N$ of intervening O VI components in the three redshift bins.

It is worth considering the potential impact of systematic effects on the weak evolution of $N(\text{O VI})$, particularly because the intergalactic compilation is formed from several heterogeneous data sets. Furthermore, the sensitivity limit of a given spectrum (the limiting O VI column density) is not straightforward to

describe by a single number, often varying from pixel to pixel, and so the limits given on Figures 3 and 4 should be considered as approximate, being set close to the column density of the weakest component detected. At $z \gtrsim 2$, the increasing density of the Ly α forest leads to an increasing probability of a given O VI component being blended, which effectively reduces the sensitivity to O VI. When considering these effects, the O VI column density distributions at both low redshift (Danforth & Shull 2008) and high redshift (Bergeron & Herbert-Fort 2005) can be described by power laws. In this sense, the observation of weak evolution in the mean $\log N(\text{O VI})$ does not indicate the existence of an underlying characteristic value of intergalactic $N(\text{O VI})$, as is the case for galactic O VI absorbers, but rather indicates that only part of the intergalactic distribution is observable. Nonetheless, Figure 4 shows that in the range $\log N > 13.5$, where all samples are expected to be complete, the distributions of $N(\text{O VI})$ in the three redshift bins show similar behavior, overlapping up to $\log N \approx 14.5$. Therefore, accounting for sensitivity differences between the data sets in the compilation reinforces the conclusion that the O VI populations are not strongly evolving.

If, for the low-redshift intergalactic sample, results are taken from Danforth & Shull (2008) instead of T08, one finds $\langle N(\text{O VI}) \rangle = 13.66 \pm 0.45$ instead of 13.78 ± 0.36 , strengthening the result that the mean $\log N$ of intergalactic O VI evolves slowly with redshift. Since Danforth & Shull present system-level (integrated) rather than component-level column densities, this indicates that the weak evolution of $\log N(\text{O VI})$ remains true whether one looks at components or systems.

The other key result from Figure 3 is that at both low and high redshifts, there is no difference in the mean O VI component column density between the intervening and proximate samples (so long as truly intrinsic absorbers are excluded; Section 3.3). At low redshift, the mean $\log N(\text{O VI})$ is 13.78 ± 0.36 for

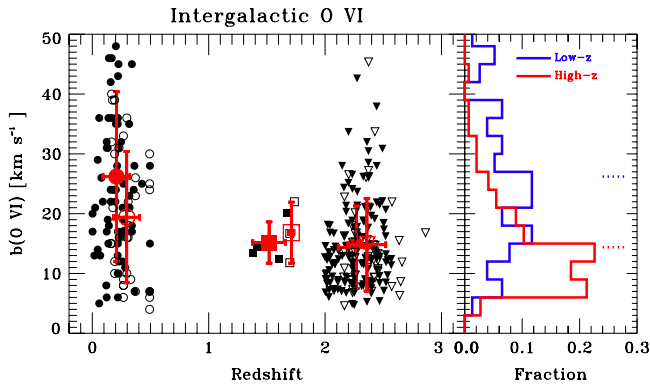


Figure 5. Line width (b -value) vs. redshift for intergalactic O VI components, using low- z data from T08, intermediate- z data from R01 and R06, and high- z data from BH05 and F08. Open symbols show proximate absorbers. The b -value distributions for the low- z and high- z intervening samples (the solid circles and solid triangles) are shown on the right-hand side. Dotted tick marks show the mean b -value of each distribution.

(A color version of this figure is available in the online journal.)

intervening components and 13.80 ± 0.41 for proximate components (T08). At high redshift, the mean $\log N(\text{O VI})$ is 13.56 ± 0.37 for intervening components (BH05) and 13.45 ± 0.36 for proximate components (F08). Note that the *incidence* dN/dz of O VI components does increase with proximity to the quasar (within $\approx 2000 \text{ km s}^{-1}$), at both low- z (T08) and high- z (F08); our point here is that $\langle N(\text{O VI}) \rangle$ does not. This finding is important because, at both low and high redshift, the intervening and proximate samples are measured in the *same* set of spectra, so the non-dependence of $N(\text{O VI})$ on proximity cannot be simply a sensitivity effect.

Despite the weak evolution in the mean $N(\text{O VI})$, there is an important difference between the low- z and high- z populations, in that the IGM O VI components are, on average, almost twice as broad at low- z than at high- z . This is shown in Figure 5, where $b(\text{O VI})$ is plotted against redshift for the intergalactic compilation, with the low- z and high- z distributions compared on the right. At low redshift, the mean and standard deviation of $b(\text{O VI})$ for intervening components is $26 \pm 14 \text{ km s}^{-1}$ (T08). At high redshift, the corresponding number is $14 \pm 7 \text{ km s}^{-1}$ (BH05). This difference is not due to resolution, since the instrumental line widths of each sample are much smaller than the mean O VI line widths: the instrumental FWHMs of 7 km s^{-1} and 6.6 km s^{-1} in the T08 and BH05 samples correspond to b -values of 4.2 km s^{-1} and 4.0 km s^{-1} , respectively.

5.1. Discussion on Origin of Intergalactic O VI

The findings that $\langle N(\text{O VI}) \rangle$ is insensitive to both redshift and quasar proximity are consistent; they show that intergalactic O VI absorbers are insensitive to the strength of the local ionizing radiation field. This result has important implications if the IGM O VI absorbers are photoionized by the EGB radiation, as is often argued (e.g., Levshakov et al. 2003b; Thom & Chen 2008b; Oppenheimer & Davé 2009, BH05), because the production of O VI by EGB photoionization (at any redshift) requires an ionization parameter $U \equiv n_\gamma/n_H$ in the range ≈ 0.1 – 1 (see Section 2). Since n_γ rises monotonically with z (Haardt & Madau 1996, 2001), the non-variation of the mean $N(\text{O VI})$ between $z = 0.2$ and $z = 2.3$ can only be explained by photoionization if n_H tracks n_γ , meaning that the average gas density in the O VI absorbers would have to be ≈ 20 times

higher at $z = 2.3$ than at $z = 0.2$. Since n_H scales as $(1+z)^3$ in an expanding universe, such a scaling may be physically reasonable (even expected). In turn, since the O VI column density in any uniform-density absorber can be written as $N(\text{O VI}) = n_H d(\text{O}/\text{H}) f(\text{O VI}) = n_\gamma d(\text{O}/\text{H}) f(\text{O VI})/U$, where d is the line-of-sight size of the cloud, the product $d(\text{O}/\text{H}) f(\text{O VI})$ would have to decrease with redshift in exact proportion to the increase in n_γ in order for EGB photoionization to work, i.e., for it to explain the non-variation of $N(\text{O VI})$. This would require the high- z absorbers to have smaller sizes, lower metallicities, or lower O VI ionization fractions (or some combination of these three) than their low- z counterparts.

On the other hand, the H02 model, in which both galactic and intergalactic O VI absorbers are formed in radiatively cooling regions of initially hot shock-heated plasma passing through the coronal regime, offers a unified explanation for the non-evolution of $N(\text{O VI})$ without any need for tunable parameters or for photoionization. Explaining the mean intergalactic $\log N(\text{O VI}) \approx 13.7$ by the cooling-flow model would require a single region with $v_{\text{cool}}(\text{IGM}) \approx 20 \text{ km s}^{-1}$, or a multi-zone arrangement such as ≈ 5 interfaces each contributing $\approx 10^{13} \text{ cm}^{-2}$. The idea that the plasma traced by intergalactic O VI is cooling rather than photoionized is further supported by the following two model-independent kinematic observations.

1. The median line width (b -value) is higher for O VI than for other (photoionized) metal lines observed in the IGM. In their high- z intervening samples, BH05 and Simcoe et al. (2002) report a median $b(\text{O VI})$ of 13 km s^{-1} and 16 km s^{-1} , respectively, whereas significantly smaller median b -values are seen for C IV ($\langle b \rangle \approx 9 \text{ km s}^{-1}$; D’Odorico et al. 2010) and N V ($\langle b \rangle \approx 6 \text{ km s}^{-1}$; Fechner & Richter 2009). At low- z , the IGM sample of Danforth & Shull (2008) has a median $b(\text{O VI})$ of 27 km s^{-1} (the T08 sample has 24 km s^{-1}), again larger than the median b -values for N V (17 km s^{-1}) and C IV (19 km s^{-1}) observed in the same redshift range (Danforth & Shull 2008).
2. Significant velocity-centroid offsets (up to 20 km s^{-1}) exist between the O VI, H I, and C IV components in a large fraction of intergalactic O VI absorbers observed at low (T08), intermediate (R01) and high (F08, Simcoe et al. 2002; Fechner & Richter 2009) redshifts. For the T08 sample, only 28 of 77 intervening O VI components (36%) are aligned with H I components.

For (the majority of) IGM absorbers with b -value differences and/or velocity-centroid offsets between O VI and other species, multi-phase solutions are required, and single-phase photoionization models cannot be used; their use will give physically irrelevant results. Even in (the minority of) IGM absorbers with aligned O VI and H I components, there is no guarantee of co-spatiality of the two ions; simulations show cases of coincident absorption arising from spatially distinct regions of gas (Oppenheimer & Davé 2009). Therefore, the observation that O VI and H I components are occasionally aligned should not be taken as proof of single-phase photoionization. Such alignments can easily be explained by interface theories (e.g., Böhringer & Hartquist 1987). Finally, the high- z mean O VI b -value of 14 km s^{-1} implies a plasma temperature $\log T < 5.27$, close to the temperature at which O VI peaks in CIE, and easily explainable by non-equilibrium CI models (e.g., Gnat & Sternberg 2007), which indicate that O VI can exist at temperatures below 10^5 K if the metallicity is high enough.

6. SUMMARY AND CONCLUSIONS

An extensive heterogeneous compilation of 775 O VI absorbers observed at high-resolution (instrumental FWHM ≤ 20 km s $^{-1}$) has been presented, covering the LISM, the disk and halo of the Milky Way, HVCs, the SMC, the LMC, starburst galaxies, the IGM from $z = 0$ to $z \approx 2.5$, DLAs at $z = 2-3$, and GRB host galaxies at $z = 2-4$, using results drawn from the literature. This compilation is divided into a galactic sample (defined by $\log N(\text{H I}) > 17$ and usually $\log N(\text{H I}) \gtrsim 20$) consisting of 447 O VI measurements in galaxies with metallicities from ≈ 0.01 solar to solar, and an intergalactic sample ($\log N(\text{H I}) < 17$) consisting of 328 O VI components covering redshifts from $z = 0$ to $z \approx 2.5$. The key observational findings are as follows.

1. For O VI measured in extended sight lines through *galactic* halos, the mean value of $\log N(\text{O VI})$ is surprisingly insensitive to metallicity (and mass), with the Milky Way halo, the LMC, the SMC, starburst galaxies, and DLAs at $z = 2-3$ all showing a mean $\log N(\text{O VI})$ within 0.4 dex of 14.5, even though they span ≈ 2 dex in $[\text{O}/\text{H}]$. While this characteristic value has been noticed before in the local universe, the new result is that it applies down to the DLA regime at $-1.6 \lesssim [\text{O}/\text{H}] \lesssim -0.6$, though there is a suggestion from the lowest-metallicity DLAs that $\langle N(\text{O VI}) \rangle$ falls off at $[\text{O}/\text{H}] < -1.6$.
2. For *intergalactic* O VI, there is surprisingly little evolution in the mean O VI component column density over cosmic time. Over the 8.2 Gyr interval between $z = 2.28$ and $z = 0.21$, the mean $\log N$ of intervening O VI components with $\log N(\text{O VI}) > 13.2$ (corresponding to rest equivalent widths > 20 mÅ) increases by only 0.17 dex, a factor of 1.5. The distributions of $N(\text{O VI})$ at $\log N > 13.5$, where the samples are complete, are shown to be insensitive to redshift. Furthermore, at both low and high redshifts, there is no difference in the mean $\log N(\text{O VI})$ between the intervening and proximate samples (so long as truly intrinsic absorbers are excluded). The insensitivity of $\log N(\text{O VI})$ to redshift and quasar proximity indicates an insensitivity to the strength of the ionizing radiation field, which (using the EGB) is a factor of ≈ 20 higher at $z = 2.28$ than at $z = 0.21$.
3. Intergalactic O VI components are, on average, almost twice as broad at low- z than at high- z , with the mean $b(\text{O VI})$ rising from 14 km s $^{-1}$ at $\langle z \rangle = 2.28$ to 26 km s $^{-1}$ at $\langle z \rangle = 0.21$.

The observation of a “characteristic” O VI column density in many diverse galactic halos covering a range of mass and metallicity is suggestive of a common origin or regulation mechanism. One such potential origin is the cooling-flow model of H02. In this model both galactic and intergalactic O VI absorbers trace regions of initially hot shock-heated plasma that are now radiatively cooling through coronal temperatures. The key advantage of this model is that it naturally explains the insensitivity of $N(\text{O VI})$ to metallicity and redshift, though it is unclear how it could explain the evolution in IGM b -values (result (3)). The general framework of the cooling-flow theory allows the regions to take several forms, including conductive, turbulent, or shocked interfaces between warm ($\sim 10^4$ K) clouds and hot ($\sim 10^6$ K) plasma. However, many such regions would have to be intersected by a typical galaxy–halo sight line to build up the characteristic galactic $N(\text{O VI})$, which is ≈ 30 times larger the column predicted in a single conductive interface.

The idea that much of the galactic O VI arises in coronal-temperature boundary layers is well known and well supported

(see references in Section 3.1). The idea that *intergalactic* O VI absorbers are also produced in such boundary layers, instead of by photoionization, is more controversial. The newly demonstrated insensitivity of the mean intergalactic $N(\text{O VI})$ to z can only be explained by photoionization if the gas density tracks the ionizing photon density, which would require the high- z O VI absorbers to have smaller sizes, lower metallicities, and/or lower ionization fractions at high- z than the low- z absorbers. While this is plausible (even expected), the kinematics of most intergalactic O VI absorbers observed at low and high redshift (specifically the b -value differences and velocity-centroid offsets observed between O VI, C IV, and H I) rule out single-phase photoionization, and require multi-phase models such as the cooling-flow scenario.

Intergalactic O VI absorbers are often discussed in the context of the elusive warm-hot IGM (WHIM), predicted by cosmological simulations to contain a substantial fraction of the present-day baryons (Cen & Ostriker 1999, 2006; Cen et al. 2001; Davé et al. 2001; Fang & Bryan 2001; Kang et al. 2005; Cen & Fang 2006). The results presented here support the view that although O VI absorbers do not directly trace the (hotter) bulk of the WHIM (Oppenheimer & Davé 2009; Tepper-Garcia et al. 2010; Smith et al. 2010), they do trace the boundary layers, where the WHIM interfaces with cooler, metal-enriched regions.

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