PROBING THE LARGE AND MASSIVE CIRCUMGALACTIC MEDIUM OF A GALAXY
AT z \sim 0.2 USING A PAIR OF QUASARS*

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ABSTRACT

We present an analysis of two O\textsc{vi} absorbers at redshift $z_{\text{abs}} = 0.227$, which were detected in the spectra of two closely spaced QSO sightlines (Q 0107–025A and B) and observed with the Cosmic Origins Spectrograph onboard the Hubble Space Telescope. At the same redshift, the presence of a single bright ($\sim 1.2 L_\odot$) galaxy at an impact parameter of $\sim 200$ kpc (proper) from both the sightlines was reported by Crighton et al. Using detailed photoionization models, we show that the high ionization phases of both the O\textsc{vi} absorbers have similar ionization conditions (e.g., $\log U \sim -1.1$ to $-0.9$), chemical enrichment (e.g., $\log Z \sim -1.4$ to $-1.0$), total hydrogen column density (e.g., $\log N_\text{HI}(\text{cm}^{-2}) \sim 19.6 - 19.7$), and line of sight thickness (e.g., $l_{\text{los}} \sim 600 - 800$ kpc). Therefore we speculate that the O\textsc{vi} absorbers are tracing different parts of same large-scale structure, presumably the circumgalactic medium (CGM) of the identified galaxy. Using sizes along and transverse to the line of sight, we estimate the size of the CGM to be $R \sim 330$ kpc. The baryonic mass associated with this large CGM as traced by O\textsc{vi} absorption is $\sim 1.2 \times 10^{11} M_\odot$. A low ionization phase is detected in one of the O\textsc{vi} systems with near-solar metallicity ($\log Z = 0.20 \pm 0.20$) and parsec scale size ($l_{\text{los}} \sim 6$ pc), possibly tracing the neutral phase of a high-velocity cloud embedded within the CGM.

Key words: galaxies: formation – quasars: absorption lines – quasars: individual (Q 0107–025A, Q 0107–025B)

Online-only material: color figures

1. INTRODUCTION

According to current theoretical models, accretion of pristine gas from the intergalactic medium (IGM; Kereš et al. 2005; Dekel et al. 2009; Bouché et al. 2010; Davé et al. 2012) and efficient galactic-scale outflows of metal-enriched gas (Springel & Hernquist 2003; Oppenheimer et al. 2010; Davé et al. 2011a, 2011b) are the two primary factors that govern the formation and evolution of galaxies. Some of the outflowing metal-enriched material eventually returns to galaxies (Oppenheimer et al. 2010). This “baryon cycle” alters the ionization and chemical conditions of the circumgalactic medium (CGM), i.e., gas in the immediate vicinity of galaxies that lies within the dark matter halos. However, due to low density of the CGM gas, direct detection of such a “baryon cycle” remains a big challenge.

The absorption lines observed in the spectra of distant quasars (QSOs) allow us to probe this tenuous CGM (Tumlinson et al. 2011b; Thom et al. 2012; Werk et al. 2013), which is otherwise not visible to us. However, the major drawback of absorption line spectroscopy is that one does not have any information about variations in the physical conditions of the absorbing gas in the direction transverse to the line of sight. Closely spaced QSO pairs (or groups) can provide useful information regarding transverse size and, therefore, the tomography of the absorber (Bechtold et al. 1994; Dinshaw et al. 1995, 1997; D’Odorico et al. 1998; Rauch et al. 2001; Petry et al. 2006; Crighton et al. 2010).

The resonant transitions of five times ionized oxygen (i.e., O\textsc{vi} $\lambda\lambda 1031, 1037$) is a useful tracer of low density diffuse gas. The high cosmic abundance of oxygen and high ionization potential ($IP = 113.9$ eV) provide O\textsc{vi} doublets with immense diagnostic power. O\textsc{vi} absorption is observed in a wide variety of astrophysical environments, e.g., IGM (Tripp et al. 2008; Thom & Chen 2008; Muzahid et al. 2011, 2012), local interstellar medium (ISM), and Galaxy halos (Savage et al. 2003; Wakker & Savage 2009), high-velocity cloud (HVC; Sembach et al. 2003), CGM (Tumlinson et al. 2011a, 2011b; Kacprzak et al. 2012; Stocke et al. 2013), etc. In particular, in a pioneering work, Tumlinson et al. (2011b) have shown that O\textsc{vi} absorption is ubiquitous in the CGM of isolated star-forming galaxies. Moreover, this highly ionized CGM gas contains considerable mass that can account for the “missing baryons” in galaxies (see also Tripp et al. 2011).

In this article we present analysis of two O\textsc{vi} absorbers at redshift $z_{\text{abs}} = 0.227$, detected in the spectra of two closely spaced quasars. Crighton et al. (2010) have identified a bright galaxy at an impact parameter of $\sim 200$ kpc at the redshift of the absorbers. We use photoionization models to understand the physical conditions of the CGM of the galaxy as probed by the O\textsc{vi} absorption. Moreover, we present a robust estimate of the CGM mass using the model predicted values of metallicity and ionization correction. This article is organized as follows. After presenting observations and data reduction in Section 2, data analysis and photoionization models are presented in Section 3. In Section 4, we discuss our results and summarize the conclusions. Throughout this article, we adopt an $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$ cosmology. The relative abundance of heavy elements is taken from Asplund et al. (2009). All the distances given are proper (physical) distances.

2. OBSERVATIONS, DATA REDUCTION

AND LINE MEASUREMENT

The well-known QSO pair (Q 0107–025A, $z_{\text{em}} = 0.960$; Q 0107–025B, $z_{\text{em}} = 0.956$; hereafter A and B) was first
observed by Dinshaw et al. (1995, 1997) with the Hubble Space Telescope (HST)/Faint Object Spectrograph (FOS) in 1994 February. Young et al. (2001) subsequently presented observations of another nearby quasar Q 0107−0232 (z_em = 0.726). Among these three quasars, the minimum angular separation is between the pair A and B (∆θ = 1.29 arcmin). This angular separation corresponds to a transverse distance of ≈280 kpc at z_abs = 0.227 for our adopted cosmology. The analysis of Lyα absorbers in this QSO triplet, based on low-resolution data, has been presented in several previous articles (e.g., Dinshaw et al. 1995, 1997; D’Odorico et al. 1998; Petry et al. 2006; Crighton et al. 2010). In this article, we will concentrate on two highly ionized absorbers detected via O vi absorption in medium resolution Cosmic Origins Spectrograph (COS) spectra. The third QSO, Q 0107−0232, is observed only with the COS/G160M grating, and therefore the spectrum does not cover O vi for the redshift of interest. We thus do not use the spectrum of Q 0107−0232 in our analysis.

The ultraviolet (UV) spectra of Q 0107−025 (A and B) were obtained using HST/COS during observation cycle-17 under program ID: 11585 (PI: Neil Crighton). These observations consist of G130M and G160M far-UV (FUV) grating integrations at medium resolution of λ/Δλ ∼ 20,000 and signal-to-noise ratio (S/N) ∼ 10 per resolution element in the wavelength range 1134−1796 Å. The properties of COS and its in-flight operations are discussed by Osterman et al. (2011) and Green et al. (2012). The data were retrieved from the HST archive and reduced using the STScI CAL/COS v2.17.2 pipeline software. The reduced data were flux calibrated. The alignment and addition of the separate G130M and G160M exposures were done using the software developed by the COS team.1 The exposures were weighted by the integration time while coadding in flux units. The reduced coadded spectra were binned by three pixels, as the COS data in general are highly oversampled (six pixels per resolution element). All measurements and analysis in this work were performed on the binned data. While binning improves the S/N of the data, measurements are found to be fairly independent of binning. Continuum normalization was done by fitting the line-free regions with a smooth lower-order polynomial. For Voigt profile fit analysis, we use non-Gaussian COS line spread function given by Kriss (2011). Multiple transitions (e.g., doublets or Lyman series lines) were always fitted simultaneously to estimate best-fitting column densities.

3. ANALYSIS

In total, there are 10 O vi systems detected in both A and B. However, only two systems (i.e., z_abs = 0.227 and 0.399) are common to both A and B. The z_abs = 0.227 system is associated with a known bright galaxy (Crighton et al. 2010). However, no galaxy information is available for the other system. In this article we focus on the z_abs = 0.227 system as observed in the spectra of A and B. Detailed analysis of the other system (i.e., z_abs = 0.399) will be presented in an upcoming article by S. Muzahid et al. (in preparation).

3.1. System at z_abs = 0.227 Toward A (System IA)

Absorption profiles of different species detected in this system are shown in the left panel of Figure 1. The Lyα and Lyβ absorption clearly show three distinct absorption components spread over ∼500 km s⁻¹. The two weak H i components

| System | log N (cm⁻²) |
|--------|-------------|
| A      |             |
| B      |             |

Notes.

1 H i associated with high-ionization phase.
2 H i associated with low-ionization phase.
3 N(C iv) calculated from W_abs given in Crighton et al. (2010).
4 Photoionization model is done for this clump.

(at relative velocities v_rel ∼ −250 and −400 km s⁻¹) are associated with C iii, N v and O vi absorption. The strongest H i component at v_rel ∼ 0 km s⁻¹ is associated with low (N ii, N iii, C ii), intermediate (C iii, Si iv), and high (N v and O vi) ionization metal lines. Crighton et al. (2010) report detection of C iv absorption in the HST/FOS spectrum with an observed equivalent width of W_abs(1548) = 0.86 ± 0.20 Å. This corresponds to log N(C iv) = 14.24 ± 0.12, assuming that the line falls on the linear part of the curve of growth. Note that the Si iv absorption is detected only in the Si iv λ 1393 transition. The other member of the doublet is blended. Moreover, the Si iv λ 1393 line could have contamination from N iii λ 989 absorption from the z_abs = 0.7286 system. Therefore, the measured N(Si iv) is strictly an upper limit. The O vi λ 1037 transition in the blue-most component (i.e., at v_rel ∼ −400 km s⁻¹) is blended with the Lyα forest. Note that C ii λ 1036 from v_rel ∼ 0 km s⁻¹ also falls at the same wavelengths. The O vi absorption is spread over ∼410 km s⁻¹ and show markedly different profile compared to those of low ions. A minimum of six Voigt profile components are required to fit the O vi doublets adequately. To simplify our photoionization model, we summed the O vi column densities of three pairs of the nearest-neighbor components (see Table 1).

The presence of several unsaturated higher-order Lyman series (up to Ly−926) lines in the strongest H i component allows robust determination of N(H i). Lyγ absorption is severely blended with the Galactic Si ii λ 1193 absorption. We modeled out the contamination while fitting the Lyman series lines. The column density and the Doppler parameter required to fit the higher-order lines (i.e., Lyδ, Ly−937, Ly−930, and Ly−926) cannot fully explain the observed Lyα and Lyβ absorption. The (blue) dotted profile in the velocity plot (see Figure 1) shows
Figure 1. Absorption profiles (black histograms) of different species in the $z_{\text{abs}} = 0.227$ system, detected in the spectrum of A (left) and B (right), are plotted in velocity. The zero velocity corresponds to the redshift of the galaxy $z_{\text{gal}} = 0.2272$. Best-fitting Voigt profiles are shown in smooth (red) curves. The (blue) dotted and (yellow) dot-dashed curves in the Lyman series lines in the left panel show the H\textsc{i} absorption associated with low- and high-ionization phases, respectively. The (blue) dotted profile is dominated by the higher order Lyman series absorption, whereas the (yellow) dot-dashed profile is dominated by the shapes of Ly\textalpha and Ly\beta absorption (see the text). Component centroids of H\textsc{i} absorption are shown by the dashed vertical lines. The ticks in the O\textsc{vi} panels mark the line centroids of O\textsc{vi} components. Unrelated absorption (blends) are marked by “x.” The (green) dotted profiles in the right panel represent the model for the blend. (A color version of this figure is available in the online journal.)

the contribution of the component that dominates the profiles of higher-order lines. This component has a Doppler parameter of $b(\text{H}\text{i}) = 26 \pm 3$ km s$^{-1}$. It is evident from the Ly\alpha and Ly\beta profiles that we need another component (preferably broad) to produce a reduced $\chi^2 \sim 1$. The (yellow) dot-dashed profile represents this broad component with $b(\text{H}\text{i}) = 48 \pm 4$ km s$^{-1}$. Because of the presence of multiple ions at different ionization states, we focus on the photoionization model for the component at $v_{\text{rel}} \sim 0$ km s$^{-1}$.

3.1.1. Photoionization Model for System 1A

Photoionization models are run using CLOUDY (Ferland et al. 1998) assuming the absorbing gas (1) has plane parallel geometry, (2) has solar relative abundances (Asplund et al. 2009) for heavy elements, and (3) is exposed to the extragalactic UV background (Haardt & Madau 1996) at redshift $z = 0.23$. Here we do not consider the effect of a galaxy/stellar radiation field, as it is negligible at this redshift at a large separation ($\sim 100$ kpc) from bright ($>L_\odot$) galaxies (see, e.g., Narayan et al. 2010). We also note that the candidate galaxy does not show any signs of recent star formation (Crighton et al. 2010).

First we model the low-ionization phase. To constrain the nature of this phase we use column densities of C\textsc{ii}, Si\textsc{ii}, N\textsc{ii}, and

| System | log $U$ | log $Z$ | log $N$(H) | log $l_{\text{los}}$ |
|--------|---------|---------|------------|-----------------|
| $1A$ (Low)$^b$ | $-3.80 \pm 0.20$ | $0.20 \pm 0.20$ | $17.5 \pm 0.2$ | $-2.2 \pm 0.4$ |
| $1A$ (High)$^c$ | $-1.10 \pm 0.25$ | $-0.95 \pm 0.25$ | $19.6 \pm 0.3$ | $2.6 \pm 0.5$ |
| $1B$ | $-0.90 \pm 0.10$ | $-1.38 \pm 0.10$ | $19.7 \pm 0.1$ | $2.9 \pm 0.2$ |

Notes.
$^a$ Size of the absorber along the line of sight.
$^b$ Parameters for low-ionization phase.
$^c$ Parameters for high-ionization phase.

Table 2: Model Parameters in the $z_{\text{abs}} = 0.227$ Systems Toward A and B

Si\textsc{iii}. The narrow H\textsc{i} component with higher $N$(H\textsc{i}) is associated with this low-ionization gas. In panel (a) of Figure 2 we show the model results computed for log $N$(H\textsc{i}) = 15.92 $\pm$ 0.08. In this plot, different curve represents loci of different low ions in the metallicity–ionization parameter (log $Z$–log $U$) plane. The (yellow) circle represents the area in the log $Z$–log $U$ plane that is allowed by data. The model parameters are summarized in Table 2. Note that N\textsc{ii} is consistent with this solution only if nitrogen is underabundant by a factor of $\sim 3$. This low-ionization
phase also produces less N \text{III} (i.e., log \( N(\text{N III}) = 12.45 \)) and C \text{III} (e.g., log \( N(\text{C III}) = 13.65 \)) than observed. However, we could not confirm the presence of N \text{III} since the relevant wavelengths are severely affected by geo-coronal Ly\(\alpha\) emission. Note that C \text{III} is an intermediate ion with contribution from both high- and low-ionization phases. This low-ionization phase does not produce any significant high-ion absorption, including Si \text{IV}.

Panel (b) of Figure 2 shows the photoionization model for the high-ionization phase of system 1A. This phase is constrained by the column densities of C \text{III}, C \text{IV}, N \text{V}, and O \text{VI}. Here we use corrected N(\text{C III}), obtained after dividing out the contribution of the low-ionization phase from the \text{C III} profile. We associate the N(\text{H I}) as measured in the broad H\text{I} component (see Table 1) with the high-ionization phase. This is a natural choice in view of the broad Ly\(\alpha\) absorber studies by Savage et al. (2011a, 2011b, 2012) and Narayanan et al. (2012), where diffuse gas traced by high ions (e.g., O \text{VI}) is usually associated with a broad Ly\(\alpha\) absorption. In Table 2 photoionization model parameters are summarized. We notice that within the allowed ranges of log \( U \) and log \( Z \), this high-ionization phase can produce a significant amount of N \text{III}, (e.g., log \( N(\text{N III}) = 13.50 \)). However, we could not confirm this because of geo-coronal Ly\(\alpha\) emission, as mentioned earlier. No singly ionized species or Si \text{III} are produced in this phase. In passing, we wish to point out that the two weak H\text{I} components, at \( v_{\text{rel}} = -250 \) and \( -400 \) km s\(^{-1}\), show ranges in log \( U \) and log \( Z \), which are very similar to this high-ionization phase.

3.2. System at \( z_{\text{abs}} = 0.227 \) Toward B (System 2B)

The velocity plot of this system is shown in the right panel of Figure 1. Compared to system 1A, this system shows weaker H\text{I} absorption. No higher-order Lyman series lines are detected beyond Ly\(\delta\). Ly\(\alpha\) shows three components, as also seen in system 1A. Ly\(\gamma\) and Ly\(\delta\) lines are blended with the Galactic Si \text{II} \( \lambda 1193 \) and O \text{III} \( \lambda 832 \) absorption from \( z_{\text{abs}} = 0.39915 \), respectively. We modeled out these blends while fitting. No metal line other than O \text{VI} and C \text{III} (only in one component) is detected in this system. The wavelengths redward to the detected C \text{III} is affected by the Galactic N \text{I} \( \lambda 1199 \) line. We note that the O \text{VI} profile, albeit showing three components as Ly\(\alpha\), is not exactly aligned with Ly\(\alpha\) profile. Similar to system 1A, the O \text{VI} absorption here is also spread over \( \sim 405 \) km s\(^{-1}\).

Si \text{IV} and N \text{V} transitions are covered by the COS spectrum; however, we do not detect any measurable absorption at the expected wavelengths. We estimate 3\(\sigma\) upper limits on \( N(\text{N V}) \) and \( N(\text{Si IV}) \) from the observed error spectrum (see Table 1). Since C \text{III} and O \text{VI} are detected only in the blue-most H\text{I} component (i.e., at \( v_{\text{rel}} \sim -120 \) km s\(^{-1}\)), we use this component for photoionization modeling.

3.2.1. Photoionization Model for System 2B

The photoionization model of the component at \( v_{\text{rel}} \sim -120 \) km s\(^{-1}\) of this system is shown in panel (c) of Figure 2. We use H\text{I}, C \text{III}, and O \text{VI} column density measurements and limits on \( N(\text{N V}) \) and \( N(\text{Si IV}) \) to constrain our model. The model parameters are summarized in Table 2. Note that the allowed values of log \( Z \) and log \( U \) are consistent with the nondetections of N \text{V} and Si \text{IV}. This single phase solution produces a C \text{IV} column density of \( N(\text{C IV}) = 13.67 \) corresponding to a \( W_{\text{abs}}(1548) = 0.19 \) Å only. This is close to the detection threshold in the FOS/G190H spectrum and therefore consistent with there being no C \text{IV} equivalent width reported for this system in Crighton et al. (2010).

4. DISCUSSIONS AND CONCLUSIONS

We have presented an analysis of two O \text{VI} absorbers (system 1A and 1B) detected in the spectra of two closely spaced QSOs (Q 0107−025A and B) at redshift \( z_{\text{abs}} = 0.227 \). The angular separation between A and B (1.29 arcmin) corresponds to a transverse separation of \( \sim 280 \) kpc at the absorber’s redshift. At the same redshift, a single bright (1.2L\text{V}) galaxy at an impact parameter of \( \sim 200 \) kpc (from both the sightlines A and B) was identified by Crighton et al. (2010). These authors have measured the star-formation rate \( > 0.45 \) M\(_{\odot}\) yr\(^{-1}\) and metallicity log \( Z \geq 0.30 \) and claim that the galaxy did not experience bursts of star formation within the last 2 Gyr. Nevertheless, the large velocity spreads (\( > 400 \) km s\(^{-1}\)) of O \text{VI} absorption in both the systems possibly suggest that the highly ionized gas could originate from galactic winds/outflows. However, as there is no recent star-formation activity in the candidate galaxy, it cannot be a fresh wind. Such an observation is consistent with “ancient outflows” as predicted in the recent simulation by Ford et al. (2013). We note that a wind material moving with a speed of 100 km s\(^{-1}\) can reach a distance of \( \sim 200 \) kpc in 2 Gyr time.
To understand the physical conditions in the absorbing gas we have built grids of photoionization models. We find that the strongest H i component in system IB can be explained with a single phase photoionization model, whereas the strongest H i component in system IA required at least two phases to explain all the detected ions. Moreover, we find remarkable similarities between the photoionization model parameters of system IB and the high ionization phase of system IA. For example, they show ionization parameter, log \( U \sim -1.1 \) to \(-0.9\); metallicity, log \( Z \sim -1.4 \) to \(-1.0\); total hydrogen column density, log \( N_H(\text{cm}^{-2}) \sim 19.6\)–19.7; and line of sight thickness, \( l_{\text{los}} \sim 600\)–800 kpc. All these suggest that the O vi absorption in systems IA and IB are possibly tracing the same large-scale structure, presumably the CGM of the galaxy identified at the same redshift.

Figure 3 shows the image of the field (left) and a schematic diagram of the CGM (right) as traced by O vi absorption. Using the estimated line-of-sight thickness and transverse separation between the two absorbers, we estimate the size of the CGM, \( R \sim 330 \) kpc. Assuming that the model-predicted density (i.e., log \( n_H \sim -4.6\)) is uniform inside the sphere of radius \( R \), we find CGM mass to be \( M_{\text{CGM}} \sim 1.2 \times 10^{11} M_\odot \). Such a large mass in the ionized CGM is also reported by Tumlinson et al. (2011b) and Tripp et al. (2011). However, all these studies assume some fiducial values of ionization correction and/or metallicity, which are not well constrained by any detailed ionization models.

Our photoionization model suggests that the low ionization phase of system IA can produce log \( N(\text{Mg} ii) = 12.87 \). Therefore this system is a weak Mg ii absorber candidate. This low-ionization phase is compact in size \( l_{\text{los}} \sim 6 \) pc and shows high metallicity (log \( Z = 0.20 \pm 0.20 \)). Note that the metallicity is \( \sim 10 \) times higher compared to that of the high-ionization phase. Such near-solar metallicity and parsec-scale size are very common features of weak Mg ii absorbers (Ribgy et al. 2002; Narayanan et al. 2008; Misawa et al. 2008). Moreover, Narayanan et al. (2008) have hypothesized that weak Mg ii absorbers are likely to be tracing gas in the extended halos of galaxies, analogous to the Galactic HVCs. It is intriguing to note that this low ionization phase is detected only in system IA but not seen in system IB. Therefore we put forward a scenario where the low ionization phase traces high density pockets, like HVCs, and the high ionization phase traces extended and diffuse CGM gas. The density difference between the two phases is more than two orders of magnitude. Thus pressure equilibrium would require temperature difference to be of the same order. However, the photoionization temperatures are not that different between the two phases, suggesting that such an absorber could be short lived.

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