HIGHLY IONIZED PLASMA IN THE HALO OF A LUMINOUS SPIRAL GALAXY NEAR $z = 0.225^*$

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ABSTRACT

We present analyses of the physical conditions in the $z$(O vi) = 0.22496 and $z$(O vi) = 0.22638 multiphase absorption systems detected in the ultraviolet Hubble Space Telescope/STIS and FUSE spectra of the quasar H 1821+643 ($m_{\text{v}} = 14.2$, $z_{\text{em}} = 0.297$). Both absorbers are likely associated with the extended halo of a $\sim 2L^*$ Sbc-Sc galaxy situated at a projected distance of $\sim 116 h^{-1}_{70}$ kpc from the sight line. The $z = 0.22496$ absorber is detected in C ii, C iii, C iv, O iii, O vi, Si ii, Si iii, and H i (Ly $\alpha$-Ly$\beta$) at $\gtrsim 3\sigma$ significance. The components of Si iii and Si ii are narrow with implied temperatures of $T \lesssim 3 \times 10^4$ K. The low and intermediate ions in this absorber are consistent with an origin in a $T \sim 10^4$ K photoionized gas with [Si/H] and [C/H] of $\sim 0.6$ dex. In contrast, the broader O vi absorption is likely produced in collisionally ionized plasma under nonequilibrium conditions. The $z$(O vi) = 0.22638 system has broad Ly $\alpha$ (BLA) and C iii absorption offset by $v = -53$ km s$^{-1}$ from O vi. The H i and C iii line widths for the BLA imply $T = 1.1 \times 10^5$ K. For non-equilibrium cooling we obtain [C/H] $\sim -1.5$ dex and N(H) = $3.2 \times 10^{18}$ cm$^{-2}$ in the BLA. The O vi, offset from the BLA with no detected H i or C iii, is likely collisionally ionized at $T \sim 3 \times 10^5$ K. From the observed multiphase properties and the proximity to a luminous galaxy, we propose that the $z = 0.22496$ absorber is an extragalactic analog of a highly ionized Galactic HVC, in which the O vi is produced in transition temperature plasma ($T \sim 10^5$ K) at the interface layers between the warm ($T < 5 \times 10^4$ K) HVC gas phase and the hot ($T \gtrsim 10^6$ K) coronal halo of the galaxy. The $z = 0.22638$ O vi-BLA absorber could be tracing a cooling condensing fragment in the nearby galaxy’s hot gaseous halo.

Key words: galaxies: halos – intergalactic medium – quasars: absorption lines – quasars: individual (H 1821+643) – ultraviolet: general

Online-only material: color figures

1. INTRODUCTION

Quasar absorption line studies as well as galaxy formation models have shown that the baryons in the extended halos of galaxies exist in the form of structures with different masses, spatial scales, densities, and temperatures. In the Milky Way, the multiphase composition of the halo is evident from the distribution of numerous neutral and warm$^1$ high-velocity gas clouds (HVCs) pressure supported by the hot and diffuse corona (Sembach et al. 2003; Collins et al. 2004; Fox et al. 2004). The sources of high-velocity gas surrounding the Milky Way include tidally stripped gas during interactions with satellite galaxies, accreting gas from the intergalactic medium (IGM), galactic scale outflows, and fragmentation from the cooling of a hot halo (see reviews by Wakker & van Woerden 1997; Richter 2006). Detecting multiphase gas in the gaseous halos of external galaxies provides an opportunity to trace these varied processes at higher redshifts. The multiphase nature of the absorber can only be fully understood through a combination of line diagnostics from low, intermediate, and high ions. Close resemblance of the physical properties with the high-velocity gas in the Galactic halo can be a crucial pointer toward the specific nature of these higher redshift systems.

Among the high ions, O vi $\lambda\lambda 1032, 1038$ lines have been of particular importance for tracing interstellar gas with $T \sim (1-3) \times 10^5$ K, due to the high relative abundance of oxygen and the large oscillator strength of the doublet lines ($f_{1032} = 0.133$, $f_{1038} = 0.067$). Ultraviolet spectroscopic observations of sight lines toward extragalactic objects have detected O vi $\lambda\lambda 1032, 1038$ absorption associated with many of the HVCs in the halo of the Milky Way. The FUSE survey of Sembach et al. (2003) found $\sim 60$–85% of the sky covered by these high-velocity O vi absorbing clouds. Some of this O vi is drawn from the same population as the neutral HVCs with N(H i) $\gtrsim 2 \times 10^{18}$ cm$^{-2}$ and thus is also detected in 21 cm radio emission above this column density limit. This neutral population has a sky covering fraction of $\sim 30\%$. The more highly ionized HVCs are detected through their absorption in the optical and UV spectra of background sources. Their non-detection in 21 cm emission constrains the H i column density to N(H i) < $2 \times 10^{18}$ cm$^{-2}$ (Sembach et al. 1999; Wakker et al. 2003; Collins et al. 2004; Ganguly et al. 2005). The O vi is an excellent tracer of collisionally ionized gas since $E > 114$ eV energies are required for its production from lower ionization stages. The observational constraints set by the ionic column density ratio of O vi with low/intermediate ions such as H i, C ii, Si ii, C iii, C iv, and other high ions such as C iv, Si iv, and N v indicate that the ionization process in the high-velocity gas

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1 Throughout this paper we use the terms warm and hot in a manner that is consistent with the traditional definition of these terms in ISM astronomy. Thus, warm refers to gas with $T \sim (0.3-3) \times 10^3$ K, and hot refers to gas with $T > 10^6$ K. For intermediate temperatures of $T \sim (0.5-10) \times 10^4$ K, we use the term transition temperature to convey that gas in this unstable temperature regime is likely not in a state of equilibrium.

2 We use the oscillator strengths and the rest-wavelengths of electronic transitions from the atomic data given in Verner et al. (1994, 1996) for $\lambda \sim 912$ Å and Morton (2000, 2003). The wavelengths are given as vacuum wavelengths rounded to the nearest natural number.
phase traced by O\textsc{v}i is dominated by collisions of electrons with ions in a plasma with \( T \sim 2 \times 10^5 \) K. The gas at this temperature is susceptible to strong radiative cooling, with the O\textsc{v}i ion also acting as a major cooling agent (Sutherland & Dopita 1993). In Galactic HVCs, the transition temperature phase with \( T \sim (1-3) \times 10^5 \) K forms from the interaction of warm photoionized gas with the hot coronal halo, and is described by a temperature intermediate to the warm and hot phases (Sembach et al. 2003; Fox et al. 2004, 2005).

Our current knowledge on the physical state of the highly ionized HVCs in the Galactic halo provides useful indicators for understanding the nature of O\textsc{v}i absorption line systems detected at higher redshift. The redshift number density \( dN/dz \sim 15 \) for absorbers with \( W_{\lambda}(O\textsc{v}i, \lambda 1032) > 30 \) mA at \( z < 0.5 \) determined from observations (Tripp et al. 2008; Danforth & Shull 2008) and supported by cosmological hydrodynamic simulations (Tumlinson & Fang 2005; Cen & Fang 2006; Oppenheimer & Davé 2009) indicates a high frequency of incidence for O\textsc{v}i absorbers at low-\( z \). Similarities in physical conditions with Galactic HVCs would suggest that at least some fraction of the population of the O\textsc{v}i absorbers are tracing high-velocity gas in external galaxies. Evidence is emerging from absorber–galaxy pair studies in quasar fields as well as more general correlation studies between absorbers and databases of galaxies from wide field surveys in favor of O\textsc{v}i absorption preferentially tracing gas in the immediate vicinity (impact parameter, \( \rho \lesssim 500 h_{71}^{-1} \) kpc) of one or more galaxies (Sembach et al. 2004; Tumlinson & Fang 2005; Stocke et al. 2006; Tripp et al. 2006; Wakker & Savage 2009; Chen & Mulchaey 2009).

Whether the absorption in all those cases is arising from a distinct gaseous structure embedded within the galaxy’s halo, from a more diffuse gaseous envelope surrounding the galaxy or from an intergalactic filament networking the individual galaxies is not always evident. In a subset of nearby O\textsc{v}i absorbers detected at high velocities with respect to the LSR, the ionization properties, galactocentric distances and location in the region of the sky surrounding the Milky Way are all consistent with an origin in the general Local Group environment rather than the Galactic halo (Sembach et al. 2003). It is therefore possible that some of the O\textsc{v}i absorbers detected at higher redshifts could also be tracing clouds within a group environment rather than the gaseous halo of one of the galaxies in the group. A detailed understanding of the physical conditions and metallicity in each absorber might help to distinguish its origin and location.

In this paper, we describe the astrophysical nature of two multiphase absorption systems detected along the sight line to the bright quasar H 1821+643 that were previously reported in Savage et al. (1998) and Tripp et al. (2000, 2008). The two absorption systems are within \( \Delta v \sim 350 \) km s\(^{-1}\) of each other. Ground-based imaging observations of this quasar field have identified galaxies in the vicinity of these absorbers (Schneider et al. 1992; Savage et al. 1998; Tripp et al. 1998). The organization of this paper is as follows. In Section 2, we provide details on the observations. Sections 3 and 4 describe the observed properties of the two absorption systems. Ground-based imaging observations of the H 1821+643 field and information on the galaxy identified in the vicinity of the absorbers are given in Section 5. Detailed investigations of the various ionization scenarios in each absorption system is considered in Section 6, followed by explanations on the astrophysical nature of these absorbers (Section 7). The main results are summarized in the last section.

2. OBSERVATIONS

In our analysis, we use \textit{STIS} and \textit{FUSE} ultraviolet spectra of the quasar H 1821+643. The \textit{STIS} observations include the higher resolution (FWHM \( \sim 7 \) km s\(^{-1}\)) FUV echelle E140M with the 0\textprime\,20 \( \times \) 0\textprime\,06 slit, and the lower resolution G230M (FWHM \( \sim 30 \) km s\(^{-1}\)) grating with the 52\textprime\,0 \( \times \) 0\textprime\,05 slit spectra that cover the wavelength intervals 1150–1730 Å and 1840–1930 Å, respectively (Prop. ID: 8165). The details of the observations are given in Tripp et al. (2000, 2008). The \textit{STIS} spectra combines a total integration of 50.932 ks in the E140M and 25.236 ks in the G230M gratings. The co-added E140M spectrum has a mean signal-to-noise ratio S/N \( \sim 18 \) per 7 km s\(^{-1}\) resolution element, and the G230M has a mean S/N \( \sim 26 \) per 30 km s\(^{-1}\) resolution element.

The \textit{FUSE} spectrum spans the 912–1187 Å wavelength range and thus covers the higher order Lyman series lines as well as a few metal lines for the absorption systems discussed in this paper. The spectral resolution is \( \sim 20 \) km s\(^{-1}\). A velocity shift was applied to the exposures in each detector segment so that the spectral features are correctly aligned (see Wakker et al. 2003; Wakker 2006, for details). The magnitude of this shift was determined by fitting the velocity centroids of low-ion absorption components in the \textit{FUSE} spectrum and aligning them with the respective low-ion components in the \textit{STIS} spectrum. The final spectrum obtained by co-adding the various \textit{FUSE} exposures with a total integration time of 280 ks was measured to have a mean S/N \( \sim 28 \) per 20 km s\(^{-1}\) resolution element for \( \lambda > 1000 \) Å and significantly lower for \( \lambda < 1000 \) Å. Certain regions of the \textit{FUSE} spectrum were affected from contamination from the interstellar absorption. We used the catalog of molecular hydrogen lines from Wakker (2006) for this sight line to distinguish possible contamination. The spectra were normalized to the level of a continuum determined using the IRAF\textsuperscript{5} SFIT procedure.

3. PROPERTIES OF THE \( z = 0.22496 \) ABSORBER

The \( z(\text{O}\textsc{v}i) = 0.22496 \) absorption system detected along the H 1821+643 sightline is plotted in Figure 1 and the line measurements are listed in Table 1. In addition to O\textsc{v}i \( \lambda\lambda 1032, 1038 \) lines, the spectra also show absorption from C\textsc{ii} \( \lambda 832, \lambda 1260 \), and Si\textsc{ii} \( \lambda 1207 \) lines. The C\textsc{iv} \( \lambda 1548, 1550 \) lines associated with this system are detected at lower resolution (FWHM \( \sim 30 \) km s\(^{-1}\)) in the \textit{STIS} G230M grating spectrum. The Si\textsc{iv} \( \lambda 1394 \) is a tentative detection, as we discuss later in this section. The H\textalpha absorption is seen in multiple Lyman series lines. The wavelength corresponding to the redshifted O\textsc{iii} \( \lambda 833 \) line is covered by the lower resolution \textit{FUSE} data. The line profile is contaminated by Si\textsc{ii} \( \lambda 1021 \) absorption from the Galactic spiral arm (the Outer Arm) at \( v_{LSR} \sim -120 \) km s\(^{-1}\). However, the strength of the unsaturated Galactic Si\textsc{ii} \( \lambda 1526 \) along this sight line suggests that the Si\textsc{ii} \( \lambda 1021 \) overlapping the O\textsc{iii} absorption is a weak feature with an estimated equivalent width of \( W \sim 30 \) mA.\textsuperscript{4} A fit to the Si\textsc{ii} \( \lambda 1526 \) high-velocity feature yields \( N(\text{Si\textsc{ii}}) \sim b(\text{Si\textsc{ii}}) \). Using these line parameters, we show in Figure 1 the expected contamination from Galactic high-velocity Si\textsc{ii} \( \lambda 1021 \) by synthesizing a line profile. Most of the absorption seen at \( \lambda \sim 1020.3 \) Å is from the O\textsc{iii} \( \lambda 832 \) feature associated with the \( z = 0.22496 \) absorber. Wherever
\textsuperscript{5} IRAF is distributed by the National Optical Astronomy Observatories, which are operated by AURA, Inc., under cooperative agreement with NSF.
\textsuperscript{4} The Si\textsc{ii} \( \lambda 1021 \) line is \( \sim 13 \) times weaker than the Si\textsc{ii} \( \lambda 1526 \) line.
possible we use measurements from fitting theoretical Voigt profiles to absorption lines. In certain cases we also quote the column density derived from the apparent optical depth (AOD) method of Savage & Sembach (1991). In Table 1, we list the apparent column density (Savage & Sembach 1991) of O III by integrating over the −70 to 58 km s\(^{-1}\) velocity interval range. For \(v > 58\) km s\(^{-1}\), there is very strong contamination from low-velocity Galactic Si ii λ 1021. The O IV λ 787 line is heavily affected by interstellar H\(_2\) absorption. The region corresponding to the redshifted Ne VIII λλ 770, 780 has low signal-to-noise ratio (S/N; ~4 per 10 km s\(^{-1}\) bin) and thus lacks the sensitivity for a relatively weak line detection. We therefore quote the Ne VIII column density as a limit based on non-detection at the 3σ significance level. The N V λλ 1238, 1242 doublet lines are also non-detections.

The complex velocity profile of H I suggests blending of different absorbing components. We use the automated Voigt profile fitting routine described in Churchill et al. (2003) to decompose the profile and determine the component structure. We assume Gaussian line spread functions corresponding to the resolving powers of the spectrographs. Applying simultaneous fits to the Ly α and higher order Lyman series lines yields a multicomponent model that is non-unique (see Table 1). The Voigt profile fits point to some of the H I components being kinematically broad, with \(b(H I) > 30\) km s\(^{-1}\). If thermally broadened, these line widths imply \(T > 3 \times 10^4\) K. In Table 1, we also list the H I line parameters obtained by excluding the saturated Ly α and Ly β lines from profile fitting. Even though the higher order Lyman lines are unsaturated, the absorption profiles are not sufficiently well resolved for a definitive identification of the H I component structure.

Multicomponent profiles are also clearly seen in O VI, Si III, and C III absorption. The individual members of the O VI λλ 1032, 1038 lines show mild differences in the component structure which are evident when we compare the apparent column density \(N_{\alpha}(v)\) profiles (see Figure 2). The difference

Figure 1. z(O VI) = 0.22496 absorber in the continuum normalized spectrum of H 1821+643. The centroids of the absorbing components for each line obtained from Voigt profile fitting are labeled with vertical tick marks. The C IV λλ 1548, 1550 and the Si IV λ 1403 lines are low resolution STIS G230M grating data. The O III λ 833 line and the Ne VIII λλ 770, 780 lines are from a low resolution FUSE spectrum. The O III line is contaminated by Galactic Si ii. The estimated contamination is shown using the synthetic line profile (red dotted line) superimposed on the spectrum. The velocity interval over which the C IV λ 1548 was integrated to obtain the apparent column density is marked. The measurements are listed in Table 1. Lines that are not part of the system are labeled and identified as follows (1) O VI λ 1038 from a metal line system at \(z = 0.1214\) (Tripp et al. 2001), confirmed by the presence of the O VI λ 1032 line at \(λ \sim 1157\) Å, Ly α and Ly β, (2), (3) and (4) Galactic Si ii lines (5) H\(_2\) line.

(A color version of this figure is available in the online journal.)
The velocity errors listed are from the profile fit code. They do not include the calibration errors of $\sim 4\, \text{km s}^{-1}$ and $\sim 5\, \text{km s}^{-1}$ respectively. (1) These measurements based on profile fits to the absorption lines are taken from Tripp et al. (2008). (2) Line parameters obtained from the profile fitting routine described in (Churchill et al. 2003). (3) Measurement based on the apparent optical depth (AOD) method of Savage & Sembach (1991). In the case of Ly $\alpha$ and C $\alpha$ 1977, the lines are strong and saturated and therefore the column densities are upper limits. (4) Limits based on non-detection at the 3$\sigma$ level. (5) The Si IV 1394 could be a marginal detection. Since the components are adequately resolved, we also quote the equivalent width for each component. The fit results are based on the assumption that the weak features at the respective velocities are Si IV. As it is an uncertain detection, we also quote a lower limit for the column density by integrating over a velocity range. (6) The components are adequately resolved, and hence we list the equivalent width for each component.

could be due to the effect of noise on one of the lines. Since the Voigt profile fitting technique is sensitive to such uncertainties, the O VI component structure is not well ascertained. The results from fitting the O VI $\lambda\lambda$1032, 1038 lines simultaneously and separately are listed in Table 1.

The multicomponent structure for an intermediate ion is best determined from the Si III $\lambda$1207 line. A Voigt profile fit decomposes the absorption into three distinct components with narrow line widths (see Table 1). There is a $> 3\sigma$ detection of a weak Si III $\lambda$1260 absorption at $v = 28.6\, \text{km s}^{-1}$ with
is fit using a broad component centered at the expected wavelength of the \( \text{Si} \text{iii} \) and \( \text{Si} \text{iv} \) feature. However, the feature appears twice as broad as the \( \text{Si} \text{ii} \) component. The blue end of the absorption is close to a column density of \( \log [N(\text{Si} \text{vi})] \approx 17 \), which implies a temperature of \( T > 10^4 \) K if the line broadening is purely thermal. The implied temperature is higher than what is plausible in photoionized gas. Due to the significant offset of the \( \text{Ly} \alpha \) from the \( \text{O} \text{vi} \) line, the \( \text{H} \text{i} \) that co-exists with the \( \text{O} \text{vi} \) phase needs to be determined separately. By integrating over a \( \Delta v \) of \( 150 \text{ km s}^{-1} \) velocity interval centered on the \( \text{O} \text{vi} \) absorption, we derive an upper limit of \( W_r(\text{Ly} \alpha) < 108 \text{ mA} \) for \( \text{H} \text{i} \) in the same ionized phase as \( \text{O} \text{vi} \). This translates into a column density of \( [N(\text{H} \text{i})] < 13.4 \). The 150 km s\(^{-1}\) velocity interval is twice the FWHM of an \( \text{H} \text{i} \) line at a \( T = 2.5 \times 10^5 \) K (based on the \( \text{O} \text{vi} \) line width) that is purely thermally broadened. A closer comparison of the \( \text{Ly} \alpha \) profile with the \( \text{O} \text{vi} \) shows that the \( \text{H} \text{i} \) absorption quickly recovers to the continuum level at positive velocities from the \( \text{O} \text{vi} \) line centroid. Thus, a more stringent upper limit of \( W_r(\text{Ly} \alpha) < 25 \text{ mA} \) and a column density of \( [N(\text{H} \text{i})] < 12.7 \) can be derived by integrating over the positive velocity interval from \( v = 0 \) to \( v = +75 \text{ km s}^{-1} \) and subsequently doubling this measurement.

At the same velocity as \( \text{O} \text{vi} \) there is no evidence for absorption from other species. The location of the \( \text{O} \text{iii} \lambda 833 \) line in the spectrum shows \( \text{O} \text{iv} \lambda 788 \) absorption from a strong metal line absorption system at \( z \approx 0.2966 \). If the relative elemental abundances in the absorber are comparable to solar,
Table 2
Properties of the $z = 0.22638$ O vi Absorption System

| Line       | $W_r$ (mA) | log $N$ (cm$^{-2}$) | $b$ (km s$^{-1}$) | $|v, +v|$ (km s$^{-1}$) | Notes |
|------------|------------|---------------------|-------------------|------------------------|-------|
| Ly $\alpha$ | $<107.0$   | $<13.4$             | $\ldots$          | $[-75, 75]$            | 1     |
| H$\alpha$  | $<25.0$    | $<12.7$             | $\ldots$          | $2 \times [0, 75]$     | 2     |
| O vi $\lambda 1032, 1038$ | $31.5 \pm 3.8$ | $13.51 \pm 0.04$ | $16 \pm 2$ | $0 \pm 1$ | 3     |
| O vi $\lambda 1032, 1038$ | $36.1 \pm 1.3$ | $13.51 \pm 0.01$ | $17 \pm 1$ | $0 \pm 1$ | 4     |
| O vi $\lambda 1032$ | $27.8 \pm 2.5$ | $13.40 \pm 0.04$ | $16 \pm 3$ | $[-30, 30]$ | 5     |
| C iv $\lambda 1335$ | $<15.5$    | $<12.9$             | $\ldots$          | $[-30, 30]$            | 6     |
| C iv $\lambda 977$ | $<15.6$    | $<12.9$             | $\ldots$          | $[-30, 30]$            | 6     |
| C iv $\lambda 1548$ | $<25.7$    | $<12.8$             | $\ldots$          | $[-30, 30]$            | 6, 7  |
| S iv $\lambda 1260$ | $<14.8$    | $<12.1$             | $\ldots$          | $[-30, 30]$            | 6     |
| S iv $\lambda 1207$ | $<13.5$    | $<11.9$             | $\ldots$          | $[-30, 30]$            | 6     |
| N v $\lambda 1403$ | $<40.4$    | $<12.9$             | $\ldots$          | $[-30, 30]$            | 6, 7  |
| N v $\lambda 1234$ | $<16.9$    | $<12.9$             | $\ldots$          | $[-30, 30]$            | 6     |
| Ne iv $\lambda 780$ | $<38.0$    | $<14.0$             | $\ldots$          | $[-30, 30]$            | 6     |
| Ne iv $\lambda 770$ | $<38.0$    | $<14.2$             | $\ldots$          | $[-30, 30]$            | 6     |

Notes. The velocity errors listed are from the profile fit code. They do not include the STIS and FUSE velocity calibration errors of $\sim 3$ km s$^{-1}$ and $\sim 5$ km s$^{-1}$ respectively. (1) These measurements are taken from Tripp et al. (2008), where a single Voigt profile is fit to the BLA absorption feature. The velocity of $v = -53 \pm 3$ km s$^{-1}$ corresponds to the velocity offset of the BLA line centroid from $z = 0.22638$, the redshift of the O vi absorber. (2) Line parameters obtained by using the automated Voigt profile fitting routine described in Churchill et al. (2003). (5) Measurement based on the apparent optical depth (AOD) method of Savage & Sembach (1991). (6) A $3\sigma$ upper limit based on non-detection. (7) Measurement based on a lower resolution STIS G230M grating spectrum.

Table 3
Properties of the Broad Ly $\alpha$ Absorption System

| Line       | $W_r$ (mA) | log $N$ (cm$^{-2}$) | $b$ (km s$^{-1}$) | $|v, +v|$ (km s$^{-1}$) | Notes |
|------------|------------|---------------------|-------------------|------------------------|-------|
| Ly $\alpha$ | $151 \pm 10.8$ | $13.52 \pm 0.02$ | $56 \pm 4$        | $-53 \pm 2$            | 1     |
| Ly $\alpha$ | $\ldots$   | $13.50 \pm 0.01$ | $51 \pm 2$        | $-50 \pm 1$            | 2     |
| Ly $\alpha$ | $\ldots$   | $12.30 \pm 0.01$ | $14 \pm 3$        | $-127 \pm 1$           | 2     |
| O vi $\lambda 1032$ | $<9.4$     | $<12.9$             | $\ldots$          | $[-160, 55]$           | 3     |
| C iv $\lambda 977$ | $17.3 \pm 5.4$ | $<12.6$             | $\ldots$          | $[-100, -35]$          | 4     |
| C iv $\lambda 977$ | $\ldots$   | $12.56 \pm 0.05$ | $28 \pm 4$        | $-52 \pm 2$            | 6     |
| C iv $\lambda 1548$ | $<31.0$    | $<12.8$             | $\ldots$          | $[-100, -35]$          | 4     |

Notes. The velocity errors listed are from the profile fit code. They do not include the STIS and FUSE velocity calibration errors of $\sim 3$ km s$^{-1}$ and $\sim 5$ km s$^{-1}$ respectively. (1) These measurements are taken from Tripp et al. (2008), where a single Voigt profile is fit to the BLA absorption feature. The velocity of $v = -53 \pm 3$ km s$^{-1}$ corresponds to the velocity offset of the BLA line centroid from $z = 0.22638$, the redshift of the O vi absorber. (2) Line parameters obtained by using the automated Voigt profile fitting routine described in Churchill et al. (2003). The Ly $\alpha$ profile is resolved into two components, where one of the components is a BLA (see Figure 1). (3) Measurement based on the apparent optical depth (AOD) method of Savage & Sembach (1991). (4) Upper limit derived by integrating the wavelength region corresponding to the redshifted O vi $\lambda 1032$ line over the velocity interval given in the table. The column density limit was derived assuming that the measurement is in the linear part of the curve of growth. (5) Line parameters obtained by Voigt profile fitting. The velocity corresponding to the centroid of the profile fit, is within $1\sigma$ of the BLA line centroid.

then we do not expect to see O iii $\lambda 833$, since the C iii $\lambda 977$ line, which is usually $\sim 9$ times stronger, is a non-detection. The wavelength corresponding to the redshifted O vi $\lambda 788$ suffers from Galactic H$_2$ contamination.

The Ly $\alpha$ absorption offset from O vi is spread over a velocity interval of $\Delta v = 190$ km s$^{-1}$. Our fitting routine derives a two component Voigt profile fit to the Ly $\alpha$ feature. Much of the H$\alpha$ absorption is arising in a broad component at $v = -50 \pm 2$ km s$^{-1}$ with log $[N(H\alpha)cm^{-2}] = 13.50 \pm 0.01$ and $b(H\alpha) = 51 \pm 2$ km s$^{-1}$. The system is therefore a broad Ly $\alpha$ absorber (BLA). The line width of the BLA implies a maximum temperature of $T = 1.6 \times 10^5$ K if the line is thermally broadened. The broad profile can also arise due to kinematic effects in the absorbing gas.

We also detect a shallow and broad C iii $\lambda 977$ absorption feature coincident in velocity with the BLA to within $1\sigma$ uncertainty. The rest-frame equivalent width of $W_r(C$ iii$\lambda 977) = 17.3 \pm 5.4$ mA, makes it a detection that is statistically significant.
Figure 3. Rest-frame velocity centered system plot for the $z$(O vi) = 0.22638 absorber in the continuum normalized spectrum of H 1821+643. The centroids of the individual absorbing components for each line derived from Voigt profile fitting are labeled with vertical tick marks. The C iv $\lambda\lambda 1548, 1550$ profiles are lower resolution ($R = \frac{\lambda}{\Delta \lambda} \sim 10,000$) STIS G230M grating data. The centroids of Ly $\alpha$ and C iii $\lambda 977$ are offset from the O vi $\lambda 1032$ line centroid by $|\Delta v| \sim -50$ km s$^{-1}$. The predicted Ly $\beta$ absorption profile corresponding to the two components seen in Ly $\alpha$ is synthesized and over-plotted (red dash-dotted line) on the relevant panel. The feature is weak and shallow and hence not detected. The measurements are listed in Tables 2 and 3. Lines that are not part of the system are labeled and are identified as follows (1) O vi $\lambda 1038$ from a metal line system at $z = 0.21337$ confirmed by the detection of O vi $\lambda 1032$, Ly $\alpha$, Ly $\beta$, and Ly $\gamma$ at the same velocity, (2) Galactic S ii $\lambda 1259$ at $v_{\text{LSR}} \sim -15$ km s$^{-1}$, (3) intrinsic C iii $\lambda 977$: (4), (5), and (6) Galactic N i $\lambda 1199$ at $v_{\text{LSR}} \sim -136, -86, -31$ km s$^{-1}$ respectively; (7) and (8) Galactic C iv $\lambda 1548$ at $v_{\text{LSR}} \sim -275, -209$ km s$^{-1}$ respectively, (9) Ly $\alpha$ at $z = 0.21674$.

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

at the 3$\sigma$ level. However, the measurement for such a shallow feature is subject to uncertain continuum placement. A single component Voigt fit shows that the C iii $\lambda 977$ line is aligned in velocity with the centroid of the BLA to within 1$\sigma$ uncertainty (see Table 3). If the BLA and C iii arise in the same gas phase, then $b$(H i) = $51 \pm 2$ km s$^{-1}$ and $b$(C iii) = $28 \pm 4$ km s$^{-1}$ imply a thermal component of $b_t$(H i) = $43$ km s$^{-1}$ and a non-thermal component of $b_{nt}$ = $28$ km s$^{-1}$ for the line widths. The thermal line width would give $T = 1.1 \times 10^5$ K for the BLA gas phase which is several times larger than the temperature of gas in photoionization equilibrium. We note that the measured $b$(C iii) is not significantly affected by instrumental broadening since the FWHM of the STIS E140M observation is only $\sim 7$ km s$^{-1}$.

The kinematic offset between the O vi and H i and their column density ratios point to the absorption arising in regions with different ionization conditions. The C iii appears as tracing the same ionized gas as the BLA, and thus can provide some constraint for the temperature and metallicity in that phase. In Section 6.2, we consider plausible ionization scenarios for this absorber and evaluate their predictions against observation.

5. GALAXIES ASSOCIATED WITH THE TWO ABSORBERS

Ground-based imaging observations of the H 1821+643 field have identified several galaxies along this sight line at the absorber redshifts. Tripp et al. (1998, 2000) report the detection
of two galaxies with spectroscopic redshifts of $z = 0.2256$ and $z = 0.2265$ in a survey centered on this quasar field. The galaxies are at angular distances of $32\,\prime\,3$ and $114\,\prime\,6$ from the line of sight to the quasar. These correspond to projected linear separations\(^5\) of $\sim 116 \, h_7^{-1}$ kpc and $\sim 412 \, h_7^{-1}$ kpc at $z = 0.2256$ and $z = 0.2265$, respectively. For brevity, we will refer to these galaxies as G and W in our discussion. Both galaxies are coincident in redshift with the absorption systems at $z = 0.22496$ and $z = 0.22638$. A more recent survey of the H 1821+643 field with the Gemini North telescope has revealed four additional galaxies near this redshift (T. M. Tripp 2009, private communication) but at several times larger impact parameters from the absorber. The quasar sight line is therefore intercepting a group of galaxies at $z \sim 0.226$.

Savage et al. (1998) derive comparable luminosities of $L_B \sim 2L_B^\odot$ for the galaxies G and W because of their similar apparent magnitudes of $g = 19.7$ and $g = 19.8$, respectively. The redshift measurements indicate a systemic velocity difference of $|\Delta v| = 158$ km s$^{-1}$ between the $z = 0.22496$ absorber and galaxy G, and a $|\Delta v| = 377$ km s$^{-1}$ with galaxy W. The $z = 0.22638$ absorber has a redshift velocity difference of $|\Delta v| = 191$ km s$^{-1}$ with respect to G and $|\Delta v| = 30$ km s$^{-1}$ with respect to W. Galaxy G is at a substantially smaller impact parameter from these absorbers compared to W. Based on the relative proximity, Savage et al. (1998) attributed the $z = 0.22496$ and the $z = 0.22638$ absorption systems to gas in the extended halo of galaxy G. Such an inference is consistent with the statistical results from past absorber–galaxy surveys (e.g., Lanzetta et al. 1995), and also with the more recent survey by Wakker & Savage (2009), where they find the O vi absorbers having an origin within $\sim 500$ kpc of $> 0.25L^\odot$ galaxies, with some substantial fraction ($\sim 40\%$) associated with the halos of $> L^\odot$ galaxies.

In Figure 4, we display a section of the WIYN R-band image of the H 1821+643 field published by Savage et al. (1998) indicating the position of galaxy G with respect to the sight line. The galaxy [R.A.(2000) = 18:21:54.5, decl.(2000) = +64:20:09.0] is located at 18\,\prime\,2 west and 26\,\prime\,7 south of the quasar, and has an angular radius of 6\,\prime\,6 that corresponds to $\sim 24$ kpc. The extended source within $\sim 4\,\prime$ from G is identified as a more distant galaxy at a redshift of $z = 0.2986$ (Schneider et al. 1992).

From the integrated H$\alpha$ luminosity, we estimate the SFR in galaxy G using the relation, SFR ($M_\odot$ yr$^{-1}$) = $7.9 \times 10^{-42}$ L(H$\alpha$) (erg s$^{-1}$) from Kennicutt (1998). This expression is a revision of Kennicutt (1983) calibration based on updated stellar models and initial mass function (IMF). The unresolved H$\alpha$ + [N ii] emission feature at $\lambda \sim 8050$ Å in the redshifted spectrum of galaxy G (see Figure 4) has an observed equivalent width of 42 Å (Schneider et al. 1992). We correct for the [N ii] contamination using the standard flux ratio H$\alpha$/[N ii] = 2.3 (Kennicutt 1992a), and also account for a 1 mag internal extinction, typical for the relevant redshift (Tresse & Maddox 1998). The L(H$\alpha$) $\sim 4.3 \times 10^{41}$ erg s$^{-1}$ thus obtained yields a SFR $\sim 3.4 M_\odot$ yr$^{-1}$, which is less compared to nearby starburst galaxies such as M 82 ($\sim 10 M_\odot$ yr$^{-1}$, O’Connell & Mangano 1978). The extinction in H$\alpha$ can be inferred directly by estimating the observed Balmer decrement in the spectrum of galaxy G. However, we are restricted in this approach due to the lack of reliable information on the equivalent width of the weak H$\beta$ emission seen at $\lambda \sim 5955$ Å. Very approximate measures from Figure 4 imply a ($H\alpha$ + [N ii])/H$\beta$ flux ratio of $\sim 2$.\(^5\) Assuming $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, and $\Omega\Lambda = 0.73$ (Wright 2006).

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\(^{5}\) Assuming $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, and $\Omega\Lambda = 0.73$ (Wright 2006).
Adapting this flux ratio and using Equation (1) in Tresse & Maddox (1998) for extinction, we determine the interstellar reddening as $A_k \sim 2.3$ mag. The Hα luminosity corrected for this reddening is $L(\text{Hα}) \sim 1.1 \times 10^{42}$ erg s$^{-1}$, corresponding to a SFR $\sim 8.3$ $M_\odot$ yr$^{-1}$. This is comparable to the SFR in certain nearby actively star-forming systems. However, we emphasize that the above estimation is at best only an upper limit on the rate of star formation particularly since galaxy G’s spectrum is devoid of strong [O iii] and other nebular emission which are characteristic of active star formation.

If the absorbers are residing in the halo of galaxy G, it is relevant to consider the galaxy as a source of ionizing radiation. The ionization fractions of H i, and low ions such as C ii and Si ii can be influenced by a galaxy’s radiation field. On the other hand, for the ionization fraction of O vi to be altered, photons with energy $E \geq 113.9$ eV are required. The radiative intensity of O and B stars at such high energies is very low due to the significant opacity from He$^+$ ionization edge at $E \geq 54.4$ eV. The O vi ionization levels will remain unaffected by the photons escaping from galaxy G, unless it contains an active nucleus which is inconsistent with its observed integrated spectrum. In Figure 5, we show an estimate of the ionizing spectrum from galaxy G at a distance of 100 kpc. The spectrum was calculated by adapting the model for the radiation escaping from the Milky Way described in Fox et al. (2005), and scaling it to the luminosity of galaxy G. This model assumes an escape fraction of 6% for the hard photons with $\lambda < 912$ Å and 22% for soft UV photons in the range 912–2460 Å. The galaxy’s ionizing flux is compared with the isotropic extragalactic background field of Haardt & Madau (2001), which has contributions from quasars as well as star-forming galaxies. The surface flux of photons$^5$ with energy $E \geq 13.6$ eV from the extragalactic radiation field at $z = 0.225$ and intercepted by the cloud surface is $\Phi = 6.3 \times 10^4$ cm$^{-2}$ s$^{-1}$ found to be a factor of $\sim$6 stronger than the ionizing flux from the galaxy at a distance of 100 kpc. The surface flux of non-hydrogen ionizing photons from the extragalactic background ($\Phi = 1.8 \times 10^5$ cm$^{-2}$ s$^{-1}$) is also substantially larger compared to the contribution from the galaxy ($\Phi = 6.7 \times 10^4$ cm$^{-2}$ s$^{-1}$).

We note that the above estimation is only an approximation. The true flux of the radiation field from galaxy G at the location of the absorber will depend on several unknown factors including the orientation of the galaxy’s disk with respect to the absorbers, the distribution of O & B stars, white dwarfs and soft X-ray sources within the galaxy contributing toward the ionizing flux, and the escape fraction of those UV photons into the halo. However, given the 100 kpc separation between the absorber and the galaxy, the ionization of the gas is likely to be dominated by the extragalactic radiation field. Hence, in the photoionization analysis of the absorbers, we use only the Haardt & Madau (2001) model for the radiation field. We discuss in Section 6.1 the extent to which the results would vary if the estimated number density of ionizing photons ($n_\gamma$) from the galaxy is also included.

6. IONIZATION CONDITIONS IN THE TWO ABSORBERS

In the following subsections, we evaluate the predictions made by photoionization and collisional ionization models using constraints set by the observed ionic column densities and line widths. Our goal is to differentiate the dominant ionization mechanism in the separate gas phases thereby gaining insight into the physical nature of the absorbers.

6.1. $z = 0.22496$ Absorber

The low ions (C ii, Si ii), intermediate ions (Si iii, C iii), and high ions (O vi, C iv) can be used to evaluate the ionization of the gas in this absorber. Photoionization calculations were performed using Cloudy (ver. C08.00; Ferland et al. 1998) with the initial assumption of solar elemental abundance ratios.$^7$ The ionizing background was modeled after the Haardt & Madau (2001) extragalactic radiation field which incorporates UV photons from quasars and star-forming galaxies. The component structure is best determined for Si iii $\lambda 1207$ (see Section 3) and hence we use it to optimize our ionization models. At

$^5$ The surface flux of hydrogen ionizing photons is calculated as $\Phi = \int F_\nu (F_\nu/\nu_0)d\nu$, where $\nu_0$ is the frequency corresponding to 13.6 eV. In the previous expression $F_\nu = 4\pi J_\nu$, where $J_\nu$ is the specific intensity in units of erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ sr$^{-1}$.

$^7$ The solar elemental abundances incorporate recent revisions and are as follows: (C/H)⊙ = −3.61 dex, (O/H)⊙ = −3.34 dex, (Si/H)⊙ = −4.46 dex (Allende Prieto et al. 2002; Holweger 2001).
the same velocity as the $v \sim 31$ km s$^{-1}$ component, there is a detection of weak Si$\text{ii}$ $\lambda$1260. The Si$\text{ii}$ and Si$\text{iii}$ likely exist in the same gas phase, as explained in Section 3. Using the $N$(Si$\text{ii}$)/$N$(Si$\text{iii}$) $\sim 0.2$, we determine the ionization parameter$^8$ for this component as $\log U = -3.0$. The ionization parameter constraint is evident from the photoionization curves displayed in Figure 6. The H$\text{i}$ component closest in velocity to the Si$\text{iii}$ component has an $N$(H$\text{i}$) = $10^{15.26}$ cm$^{-2}$. Assuming that all of this H$\text{i}$ is associated with the same gas phase as Si$\text{iii}$, we derive a silicon abundance of [Si/H] $= -0.62$ dex. Synthetic absorption profiles based on the column densities derived from the photoionization model with $\log U = -3.0, [Z/H] = -0.62$ dex are shown in Figure 7. The predicted C$\text{ii}$ $\lambda$1335 and C$\text{iii}$ $\lambda$977 for the $v = 31$ km s$^{-1}$ component are also consistent with the data, which suggests a carbon abundance of $\sim 0.6$ dex (see Figure 6). For this component, the above model yields a total hydrogen column density of $N$(H$\text{i}$) = $3.9 \times 10^{17}$ cm$^{-2}$, a volume density of $n_\text{H} = 2.5 \times 10^{-3}$ cm$^{-3}$, a photoionization equilibrium temperature of $T = 1.3 \times 10^4$ K, and a gas pressure of $p/K = 71$ K cm$^{-3}$. The density and total hydrogen column density imply a path length of $L = 0.05$ kpc for the gas cloud probed by this absorption component. We find that the predicted O$\text{vi}$ column density in this photoionized gas phase (see Figure 6) is $\sim 0.5$ dex smaller than the observed value.

There is uncertainty in the Si and C abundances, dominated by systematic uncertainties associated with the hydrogen profile modeling and the assumptions inherent in Cloudy photoionization calculations. The $N$(H$\text{i}$) used to constrain the metallicity is based on the simplistic assumption that the profile structure, as seen in the higher order Lyman lines, is well represented by a two-component Gaussian (see Figure 7). The error values given by the profile fitting procedure do not adequately account for the uncertainty in the H$\text{i}$ component structure. The true $N$(H$\text{i}$) associated with the $v = 31$ km s$^{-1}$ Si$\text{iii}$ is possibly within 0.2 dex of the fit measurement. Also, the uncertain shape of the ionizing UV background from quasars results in a $\sim 0.3$ dex uncertainty in the metallicity predicted by Cloudy (Aracil et al. 2006). Considering these systematics, we estimate the uncertainty in the Si and C abundances to be 0.4 dex.

For the $v \sim 3$ km s$^{-1}$ Si$\text{iii}$ component, there is weak C$\text{ii}$ $\lambda$1335 absorption detected. The corresponding C$\text{ii}$ is saturated such that $N$(C$\text{ii}$)/$N$(C$\text{iii}$) $< 0.3$. The ratio provides a lower limit of $\log U > -3.0$, corresponding to a density upper limit of $n_\text{H} < 1.9 \times 10^{-3}$ cm$^{-3}$ (see Figure 6), comparable to the density determined for the 31 km s$^{-1}$ component. This ionization parameter is also consistent with $N$(Si$\text{ii}$)/$N$(Si$\text{iii}$) $\geq 0.4$. We note that the C$\text{ii}$ is a very weak feature, and the Si$\text{iv}$ only a tentative detection (see Section 3). Hence the respective ionic column density ratios are, at best, limits. For the absorbing component at $v \sim -39$ km s$^{-1}$ the constraint on $\log U$ is weak due to the non-detection of C$\text{ii}$ or Si$\text{ii}$. Assuming solar relative elemental abundance for carbon and silicon, the $N$(C$\text{iii}$)/$N$(Si$\text{iii}$) $\sim 20$ is recovered at $\log U \sim -2.2$ (see Figure 6). Due to its complicated velocity profile, the H$\text{i}$ corresponding to the $v \sim 3$ km s$^{-1}$ and $v \sim -39$ km s$^{-1}$ components are uncertain and hence an abundance estimation is not meaningful.

The strength of O$\text{vi}$ relative to C$\text{iv}$ and the absence of Si$\text{iv}$ and N$\text{v}$ absorption indicate that this separate phase is

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$^8$ Ionization parameter is defined as the ratio of the number density of photons with $E \geq 13.6$ eV to the hydrogen density, $U = n_\gamma/n_\text{H}$. 

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**Figure 6.** Expected column densities from photoionization models for the $v \sim 31$ km s$^{-1}$ component seen in Si$\text{iii}$ and Si$\text{ii}$ of the $z = 0.22496$ absorber in the spectrum of H1821+643. The $N$(H$\text{i}$) = $10^{15.26}$ cm$^{-2}$ is the H$\text{i}$ that is coincident in velocity with this component (see Table 1). The ionizing background is from the Haardt & Madau (2001) model for the relevant redshift and includes ionizing photons from quasars and star-forming galaxies. The model that best fits the ionization calculations. The modeling and the assumptions inherent in Cloudy photoionization calculations. The $N$(H$\text{i}$) used to constrain the metallicity is based on the simplistic assumption that the profile structure, as seen in the higher order Lyman lines, is well represented by a two-component Gaussian (see Figure 7). The error values given by the profile fitting procedure do not adequately account for the uncertainty in the H$\text{i}$ component structure. The true $N$(H$\text{i}$) associated with the $v = 31$ km s$^{-1}$ Si$\text{iii}$ is possibly within 0.2 dex of the fit measurement. Also, the uncertain shape of the ionizing UV background from quasars results in a $\sim 0.3$ dex uncertainty in the metallicity predicted by Cloudy (Aracil et al. 2006). Considering these systematics, we estimate the uncertainty in the Si and C abundances to be 0.4 dex.

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The strength of O$\text{vi}$ relative to C$\text{iv}$ and the absence of Si$\text{iv}$ and N$\text{v}$ absorption indicate that this separate phase is
which corresponds to the weak Si vi phase given by the component line widths in the photoionized phase of this absorber due to Na heavily ionized. The lower resolution ($R = \lambda/\Delta\lambda \sim 10,000$, FWHM $\sim 30$ km s$^{-1}$) G230M grating spectrum does not resolve the component structure in the C iv $\lambda\lambda1548,1550$ lines. To a first approximation, we can determine the ionization conditions in the O vi gas phase by comparing the integrated apparent optical depth column densities of O vi and C iv. The ratio $N_{e}(\text{C iv})/N_{e}(\text{O vi}) \sim 0.2$ ratio is recovered through photoionization at an ionization parameter of $log U \sim -0.8$ which corresponds to $n_{H} = 1.1 \times 10^{-3}$ cm$^{-3}$. If we assume that this O vi absorbing gas has the same abundances as the Si iii in the 31 km s$^{-1}$ component, then a log $U = -0.8$ model yields $N(\text{H}) = 7.9 \times 10^{16}$ cm$^{-2}$, $n_{H} = 1.1 \times 10^{-3}$ cm$^{-3}$, $T = 3.3 \times 10^{6}$ K, $\rho/K = 8.2$ cm$^{-3}$ K, and a path length of $\sim 230$ kpc. Such a large path length and low pressure is unrealistic given the close kinematic coupling between O vi and the lower ionization gas traced by Si iii, C iii, Si ii, and C ii which has higher pressure and much smaller physical size. Increasing the metallicity in the O vi gas to solar would still yield a path length of $\sim 60$ kpc, which is still $\sim 3$ orders of magnitude bigger than the size of the lower ionization gas clouds.

A more realistic scenario is the production of O vi through collisional processes in a higher temperature gas. Collisional ionization equilibrium (CIE) models predict the measured $N_{e}(\text{C iv})/N_{e}(\text{O vi}) \sim 0.2$ at $T \sim 2 \times 10^{5}$ K. Such a CIE temperature is consistent with the absence of Si iv and N v, and also $N_{e}(\text{C iii})/N_{e}(\text{O vi}) \gtrsim 0.5$ (assuming solar abundance ratios). However, gas in the temperature range of $T \sim (1-5) \times 10^{5}$ K undergoes rapid radiative cooling and will be displaced from a state of thermal equilibrium. Non-equilibrium collisional ionization processes thus become important for the production of O vi in this absorber.

In multiphase gaseous environments such as the Galactic HVCs and the local interstellar medium (LISM), non-equilibrium collisional ionization models have been particularly successful in explaining the origin of O vi (Sembach et al. 2003; Fox et al. 2004; Savage & Lehner 2006). In the next section, we compare the $z = 0.22496$ absorption system to Galactic high-velocity gas where the origin of O vi is better understood. The proximity of the $z = 0.22496$ absorber to a luminous galaxy (see Section 5) makes such a comparison relevant.

6.1.1. The $z = 0.22496$ Absorber as an Extragalactic Analog of Galactic HVC

Galactic HVCs detected in high ions are multiphase systems with a mix of warm ($T \sim 10^{4}$ K) gas traced by low/intermediate ions and a higher ionization gas phase at a higher temperature ($T \sim 10^{5}$ K) traced primarily by O vi and C iv (Sembach et al. 2000, 2003; Fox et al. 2004, 2005; Ganguly et al. 2005). The higher temperature is usually evident from the line width of O vi components which are, on average, broader than the components seen in low/intermediate ions. The $N(\text{O vi})/N(\text{H i})$ in Galactic HVC samples span a wide range ($\sim 10^{-6}$--$10^{-2}$), even though the observed $N(\text{O vi})$ is usually within 1 dex of $\sim 10^{13}$ cm$^{-2}$, suggestive of entirely different ionization mechanisms operating in the H i and O vi gas phases (Fox et al. 2005). In HVCs, photoionization under the influence of an extragalactic radiation field or a radiation field escaping from the Galaxy is found to be sufficient to explain the observed strength of low/intermediate ions, whereas the $N(\text{O vi})$ (and to some extent C iv) is inconsistent with a similar origin (e.g., Fox et al. 2004, 2005). The overall properties of the highly ionized Galactic HVCs are remarkably similar to what we find for the $z = 0.22496$ absorber (see Section 6.1). The photoionized components in Galactic HVCs have densities [$n_{H} \sim (1-10) \times 10^{-3}$ cm$^{-3}$], and physical sizes [$L \sim (20-500)$ pc] which are in the range of what we derive for the C ii, Si ii, Si iii phase in the $z = 0.22496$ absorber. Collisional ionization models for Galactic HVCs, with temperatures typically of $T \sim 1.7 \times 10^{5}$ K well reproduce the observed ionic ratios such as $N_{e}(\text{C iii})/N_{e}(\text{O vi})$ (Fox et al. 2006). This is also consistent with the temperature for the O vi phase given by the component line widths in the $z = 0.22496$ absorber.

Based on careful analysis of the close kinematic association of O vi absorption with low/intermediate metal ions, and the column density ratio predictions provided by various ionization models, several authors have proposed that the Galactic high-velocity O vi is most likely produced at interface layers between warm gas clouds and a hot exterior medium (e.g., Sembach et al. 2003; Fox et al. 2004, 2005). In the halo, the hot exterior medium corresponds to the diffuse [$n_{H} \sim (1-10) \times 10^{-3}$ cm$^{-3}$] coronal plasma with $T \sim (1-3) \times 10^{6}$ K extending to galactocentric distances of $R > 70$ kpc. The steep temperature gradient between the warm photoionized HVC phase and the hot exterior gas gives way to heat transport through electron collisions resulting in transition temperatures $T \sim (1-6) \times 10^{5}$ K at the interface layers (Savage & Lehner 2006). In the interface layers equilibrium ionization conditions are unlikely and the ionization state of the gas cannot be described using a single temperature. Among the various nonequilibrium processes, conductive interface models (Boehringer & Hartquist 1987;
Borkowski et al. 1990) have been particularly successful in reproducing the range of high ion column density ratios, and also the velocity offsets between the absorption from the warm phase and the interface gas (Fox et al. 2004, 2005). The high ion ratios of \( N_\alpha(C\,\text{iv})/N_\alpha(O\,\text{vii}) \approx 0.2, N_\alpha(N\,\text{v})/N_\alpha(O\,\text{vii}) < 0.1, N_\alpha(Si\,\text{iv})/N_\alpha(O\,\text{vii}) < 0.04 \) which we measure for the \( z = 0.22496 \) absorber are fully consistent with a conductive interface model (see Figure 12 of Fox et al. 2005). A single conductive interface layer is predicted by the models to yield a \( N(O\,\text{vii}) \approx 10^{13} \text{ cm}^{-2} \). This value is \( \sim 1.5 \text{ dex} \) lower than the observed integrated \( O\,\text{vii} \) column density. In the context of Galactic HVCs, Sembach et al. (2003) have shown that higher values were optimized to converge on the measured integrated \( O\,\text{vii} \) column density. HVC structures are understood to be confined by the boundary between the warm photoionized high-velocity gas and the interface gas (Fox et al. 2004, 2005). The high ionization parameter, the models predict the gas column density ratio is constrained to be a multiphase HVC system embedded within the halo of radius \( R_\text{G} \). For a given combination of metallicity and ionization parameter, the models were optimized to converge on the measured \( N(O\,\text{vii}) \). The photoionization results are tabulated in Table 4. In the \( O\,\text{vii} \) phase, the \( H\,\text{i} \) to \( O\,\text{vii} \) column density ratio is constrained to be \( N(H\,\text{i})/N(O\,\text{vii}) < 10^{-1} \) (see Table 2). Figure 8 is a visualization of the \( H\,\text{i} \) line profiles predicted by the various photoionization models. As these synthetic profiles show, even for a very high ionization parameter limit such as \( \log U < -0.1 \), at \( [Z/H] = -0.5 \text{ dex} \), \( H\,\text{i} \) is overproduced compared to data, evident from the excess absorption at positive velocities with respect to the \( O\,\text{vii} \) line centroid. Moreover, for a \( \log U < -0.1 \), the implied density is so low that it results in a very large path length (\( d \approx 0.4 \text{ Mpc} \)) for the absorbing region. The Hubble flow broadening from such a large path length is going to be a factor of \( \sim 1.5 \) larger than the measured \( b(O\,\text{vii}) = 16 \pm 2 \text{ km} \text{ s}^{-1} \).

A photoionization solution simultaneously satisfying the path length constraint as well as the \( N(H\,\text{i})/N(O\,\text{vii}), N(C\,\text{iii})/N(O\,\text{vii}), \) and \( N(C\,\text{iv})/N(O\,\text{vii}) \) limits is possible only at \( [Z/H] \gtrsim 0 \text{ dex} \). Even at solar metallicity, the ionization parameter in the \( O\,\text{vii} \) gas phase is limited to a narrow range of \( -0.8 < \log U < -0.1 \), corresponding to a very low gas density of \( n_\text{G} \approx 10^{-6} \text{ cm}^{-3} \). Even in these models, the size of the \( O\,\text{vii} \) absorbing region is predicted to be \( d \gtrsim 10 \text{ kpc} \) (see Table 4). A 10 kpc path length seems incompatible with the relatively symmetric and narrow absorption profile of \( O\,\text{vii} \). The models estimate an equilibrium temperature of \( T \sim 3 \times 10^{4} \text{ K} \) which suggests that \( >90\% \) of the \( O\,\text{vii} \) line width must be due to non-thermal effects.

In summary, a photoionization origin is unrealistic for the \( O\,\text{vii} \) in the \( z = 0.22638 \) absorber. The very low densities predicted for photoionized medium \( n_\text{H} \approx 10^{-6} \text{ cm}^{-3} \) in order to not overproduce \( C\,\text{iii}, C\,\text{iv}, \) and \( H\,\text{i} \) from the same phase as \( O\,\text{vii} \), results in large absorber sizes for \( [Z/H] \leq 0 \) dex. A large path length for the absorbing region is inconsistent with the symmetric and relatively narrow line profile of \( O\,\text{vii} \), which shows no direct evidence of subcomponent structure.

6.2.2. Can the \( O\,\text{vii} \) be Collisionally Ionized?

A second possibility is the production of \( O\,\text{vii} \) through the collision of electrons with ions in a medium with \( T \gtrsim 10^{5} \text{ K} \). Thom & Chen (2008) show that \( N(O\,\text{vii})/N(H\,\text{i}) > 1 \) is possible in collisionally ionized gas even when the metal abundance is low. In the \( z = 0.22638 \) \( O\,\text{vii} \) absorber, the temperature implied by the \( O\,\text{vii} \) line width is \( T \lesssim 3.1 \times 10^{5} \text{ K} \) (i.e., \( T \lesssim 10^{5.3} \text{ K} \)), which is close to the temperature at which \( O\,\text{vii} \) ionization fraction peaks under CIE. If line broadening is predominantly thermal, then the temperature upper limit is sufficiently large to produce detectable amounts of \( O\,\text{vii} \). The temperature upper limit is also consistent with the non-detection of \( C\,\text{iii}, C\,\text{iv}, \) and \( Ne\,\text{vii} \) ions. The non-detection of \( C\,\text{iii} \) and \( C\,\text{iv} \) at the same velocity as \( O\,\text{vii} \) can be used to place a lower limit on the gas temperature. For \( T > 10^{5} \text{ K} \), the \( C\,\text{iii} \) ionization fraction rapidly declines. In CIE, the \( N(O\,\text{vii}) > N(C\,\text{iii}) \) and \( N(O\,\text{vii}) > N(C\,\text{iv}) \) for \( T \gtrsim 2 \times 10^{5} \text{ K} \). Therefore, we can limit the temperature in the \( O\,\text{vii} \) gas phase to a narrow range of \( (2.0–3.1) \times 10^{5} \text{ K} \) (i.e., \( 10^{5.3} \text{ K}–10^{5.5} \text{ K} \)). In that range of temperatures, most of the oxygen will be in the \( O\,\text{viii} \) state. However, the wavelength corresponding to the redshifted \( O\,\text{vii} \) absorption is contaminated by very strong Galactic \( H\,\text{ii} \) absorption, and thus we lack this crucial additional constraint.

For any given combination of \( N(H\,\text{i}) \) and \( [Z/H] \), there is a unique temperature at which the observed value of \( N(O\,\text{vii}) \) is recovered, assuming CIE conditions. For example, as shown in Figure 9, at \( N(H\,\text{i}) = 10^{12.6} \text{ cm}^{-2} \) and \( [Z/H] = -0.9 \) dex, the measured \( N(O\,\text{vii}) \) is reproduced by the CIE model at a temperature of \( T = 3.2 \times 10^{5} \text{ K} \), which also satisfies the \( N(C\,\text{iv}) < 10^{12.8} \text{ cm}^{-2} \text{ limit} \). The \( N(C\,\text{iii}) \) predicted by the
Figure 8. Synthetic Ly α absorption profiles based on results from photoionization models for a range of log $U$ and metallicities of 1/3 solar (left panel) and solar (right panel) are over-plotted on the data. The models were optimized to recover the measured O vi column density. The predictions of the models become consistent with the H i column density limit only for high values of ionization parameter such as log $U > -0.5$. However, such high ionization parameters result in unrealistically large path lengths for the O vi absorbing region (see Table 3).

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

Table 4

Summary of the Photoionization Modeling Results for the $z = 0.22638$ O vi Absorption

| [Z/H] | U (dex) | N(H) (dex) | N(H i) (dex) | N(O vi) (dex) | N(C ii) (dex) | $n_{\text{H}}$ (cm$^{-3}$) | T (K) | p/k (K cm$^{-3}$) | L (kpc) | Comments |
|-------|---------|------------|--------------|---------------|---------------|-----------------|-------|-----------------|--------|----------|
| $-0.5$ | $-2.0$  | 20.40      | 16.97        | 13.51         | 16.20         | 15.18           | $1.88 \times 10^{-4}$ | $1.40 \times 10^{4}$ | 2.63    | 434      | H i, C m, C iv over produced, large path length |
| $-0.5$ | $-1.0$  | 18.25      | 13.65        | 13.51         | 13.21         | 13.19           | $1.88 \times 10^{-5}$ | $2.80 \times 10^{4}$ | 0.53    | 31       | H i, C m, C iv over produced |
| $-0.5$ | $-0.7$  | 18.10      | 13.12        | 13.51         | 12.43         | 12.65           | $9.41 \times 10^{-6}$ | $3.30 \times 10^{4}$ | 0.31    | 43       | H i over produced |
| $-0.5$ | $-0.5$  | 18.10      | 12.90        | 13.51         | 11.94         | 12.32           | $5.93 \times 10^{-6}$ | $3.83 \times 10^{4}$ | 0.23    | 69       | H i over produced |
| $-0.5$ | $-0.3$  | 18.25      | 12.79        | 13.51         | 11.47         | 12.02           | $3.74 \times 10^{-6}$ | $4.49 \times 10^{4}$ | 0.17    | 154      | Large path length |
| $-0.5$ | $-0.1$  | 18.50      | 12.79        | 13.51         | 11.01         | 11.74           | $2.36 \times 10^{-6}$ | $1.40 \times 10^{4}$ | 0.03    | 433      | Large path length |
| $-0.3$ | $-2.0$  | 20.12      | 16.73        | 13.51         | 16.12         | 15.12           | $1.88 \times 10^{-4}$ | $1.25 \times 10^{4}$ | 2.35    | 228      | H i, C m, C iv over produced, large path length |
| $-0.3$ | $-1.0$  | 18.03      | 13.46        | 13.51         | 13.18         | 13.22           | $1.88 \times 10^{-5}$ | $2.52 \times 10^{4}$ | 0.47    | 19       | H i, C m, C iv over produced |
| $-0.3$ | $-0.7$  | 17.84      | 12.91        | 13.51         | 12.41         | 12.66           | $9.41 \times 10^{-6}$ | $3.08 \times 10^{4}$ | 0.29    | 24       | H i over produced |
| $-0.3$ | $-0.5$  | 17.87      | 12.69        | 13.51         | 11.93         | 12.33           | $5.93 \times 10^{-6}$ | $3.58 \times 10^{4}$ | 0.21    | 41       | H i over produced |
| $-0.3$ | $-0.3$  | 18.02      | 12.58        | 13.51         | 11.47         | 12.02           | $3.74 \times 10^{-6}$ | $4.30 \times 10^{4}$ | 0.16    | 91       | Large path length |
| $-0.3$ | $-0.1$  | 18.30      | 12.58        | 13.51         | 11.00         | 11.73           | $2.36 \times 10^{-6}$ | $5.33 \times 10^{4}$ | 0.13    | 274      | Large path length |
| $0.0$  | $-2.0$  | 19.73      | 16.41        | 13.51         | 16.03         | 15.01           | $1.88 \times 10^{-4}$ | $1.40 \times 10^{4}$ | 2.63    | 93       | H i, C m, C iv over produced, large path length |
| $0.0$  | $-1.0$  | 17.67      | 13.16        | 13.51         | 13.13         | 13.24           | $1.88 \times 10^{-5}$ | $2.17 \times 10^{4}$ | 0.41    | 8        | H i, C m, C iv over produced |
| $0.0$  | $-0.7$  | 17.50      | 12.61        | 13.51         | 12.38         | 12.68           | $9.41 \times 10^{-6}$ | $2.76 \times 10^{4}$ | 0.26    | 11       | Acceptable, but marginal |
| $0.0$  | $-0.5$  | 17.55      | 12.40        | 13.51         | 11.93         | 12.36           | $5.93 \times 10^{-6}$ | $3.29 \times 10^{4}$ | 0.20    | 19       | Acceptable |
| $0.0$  | $-0.3$  | 17.70      | 12.28        | 13.51         | 11.47         | 12.03           | $3.74 \times 10^{-6}$ | $4.09 \times 10^{4}$ | 0.15    | 43       | Acceptable |
| $0.0$  | $-0.1$  | 18.02      | 12.30        | 13.51         | 11.02         | 11.75           | $2.36 \times 10^{-6}$ | $5.40 \times 10^{4}$ | 0.13    | 144      | Large path length |

Notes. The predicted model column densities and other physical parameters at different metallicities and ionization parameters in order to recover the observed value of O vi column density under photoionization equilibrium conditions. The number density of ionizing photons with $h \nu > 13.6$ eV is estimated from the Haardt & Madau (2001) ionizing background radiation field to be $n_{\gamma} = 1.88 \times 10^{-6}$ cm$^{-3}$. The elemental abundance for C and O are assumed to be solar, with [C/H] = −3.61 and [O/H] = −3.31 as described in Cloudy (ver. 08) and Allende Prieto et al. (2002).

CIE model is marginally consistent with the 3σ upper limit. Since the $N(H i) = 10^{12.6}$ cm$^{-2}$ is only an upper limit for H i at the same velocity as O vi (see Table 2), the metallicity estimation is indefinite. Also, the CIE model assumes a (C/O) relative elemental abundance ratio of solar, which is also not well constrained by the data.
Figure 9. CIE (solid) and non-CIE (dash-dotted) model column density predictions for C\textsc{iii} (blue), C\textsc{iv} (green), and O\textsc{vi} (red) as a function of temperature. The non-CIE model is for an isochorically cooling gas. The H\textsc{i} column density in these models is fixed to the estimated 3$\sigma$ upper limit of N(H\textsc{i}) = 10$^{12.6}$ cm$^{-2}$ (see Table 2). The measured O\textsc{vi} column density is represented by the horizontal solid line. The C\textsc{iii}, and C\textsc{iv} upper limits based on non-detection are marked using dotted and dashed lines, respectively. The lower and upper temperature limits of 10$^{3.3}-10^{5.5}$ K, allowed by the data are marked by the two vertical dash-dotted lines. Both CIE and non-CIE conditions appear to be consistent with the measurements. At a metallicity of $-0.9$ dex, the CIE and non-CIE ion fractions for O\textsc{vi} are not significantly different from each other.

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

The $T = (2.0-3.1) \times 10^5$ K predicted for the O\textsc{vi} phase is in the temperature range where radiative cooling is efficient. Departures from CIE are expected due to rapid metal line cooling. In Figure 7, we show the O\textsc{vi}, C\textsc{iii}, and C\textsc{iv} column densities at [Z/H] = $-0.9$ dex for an isochorically cooling gas as computed by Gnat & Sternberg (2007). The ionization fractions of O\textsc{vi} as a function of temperature does not show significant departure from CIE at $-0.9$ dex metallicity. Both the CIE and non-CIE predictions for the C\textsc{iii} and C\textsc{iv} column densities are also consistent with their respective upper limits. From the available column density information alone it is difficult to conclude whether the gas is in ionization equilibrium or not.

6.2.3. The BLA Gas Phase

The H\textsc{i} at $v = -53$ km s$^{-1}$ from the O\textsc{vi} $\lambda\lambda$1032, 1038 lines is a BLA (see Section 4). The temperature implied by the $b(H\textsc{i}) = 51 \pm 2$ km s$^{-1}$ is $T \sim 1.6 \times 10^5$ K, assuming pure thermal broadening. There is a formal 3$\sigma$ detection of C\textsc{iii} $\lambda977$ line, but no O\textsc{vi}, at the velocity of BLA. If the H\textsc{i} and C\textsc{iii} are tracing the same gas, then $b(H\textsc{i})$ and $b(C\textsc{iii})$ imply $T \sim 1.1 \times 10^5$ K. This value is a factor of $\sim 4$ higher than the temperatures attained through photoionization. Nonetheless, we explore a range of parameter space in metallicity and log $U$ to evaluate the feasibility of photoionization in the BLA phase. The predictions of the various models are tabulated in Table 5. It is evident that photoionization equilibrium models do not succeed in simultaneously explaining the H\textsc{i}, C\textsc{iii}, C\textsc{iv}, and O\textsc{vi} column density measurements and limits. More importantly, the predicted temperatures are inconsistent with the expected value from the H\textsc{i} and C\textsc{iii} line widths. It is possible for the C\textsc{iii} $\lambda977$ line to be a blend of unresolved components of smaller line widths. However, it is difficult to discriminate such a multicomponent structure in the present data, since the C\textsc{iii} feature is very shallow and the S/N of the data inadequate.

The temperature given by $b(H\textsc{i})$ and $b(C\textsc{iii})$ suggest collisional ionization to be a more realistic scenario. At $T = 1.1 \times 10^5$ K, the N(C\textsc{iii}) predictions made by CIE and non-CIE models differ by $\sim 0.4$ dex. For the given $N(H\textsc{i})$ and temperature, the non-CIE models estimate the C abundance to be [C/H] $\sim -1.5$ dex, whereas the CIE models estimate the abundance as $\sim -1.8$ dex. At the temperature given by the line widths, radiative cooling can be rapid leading to significant departures from equilibrium ionization fractions. Hence the non-CIE abundance estimation is preferred.

In Figure 10, we display the non-CIE ionization curves for C\textsc{iii}, C\textsc{iv}, and O\textsc{vi} in an isochorically cooling gas at a chosen metallicity (Gnat & Sternberg 2007). For comparison, the corresponding CIE predictions are also shown. At [C/H] = $-1.5$ dex and $T = 1.1 \times 10^5$ K, the non-CIE model is able to reproduce the observed C\textsc{iii} to H\textsc{i} column density ratio. The $f(H\textsc{i}) = N(H\textsc{i})/N(H\textsc{iii}) \sim 10^{-5}$ ionization correction given by the non-CIE model results in a total hydrogen column density of $N(H) \sim 3.2 \times 10^{18}$ cm$^{-2}$, signifying the BLA to be a substantial baryon reservoir.

6.2.4. Physical Nature of the $z = 0.22638$ Absorber

It is evident from the analysis presented in the foregoing two sections that the O\textsc{vi} and the H\textsc{i} in the $z = 0.22638$ absorber are tracing separate collisionally ionized gas phases. The absorber is situated in the vicinity of a luminous galaxy (see Section 5), and thus it could potentially be a gaseous structure embedded within the galaxy’s extended halo. The kinematic proximity of this system to the higher column density $z = 0.22496$ absorber also leads to this possibility (see Section 6.1.1). However, the O\textsc{vi} in this absorber might not be produced in a typical warm–hot gas interface as in the multiphase Galactic HVCs, since we do not detect a warm gas phase for this absorber. At the boundary between the BLA gas and the hot corona of galaxy G, transition temperature gas would still form due to the temperature gradient. The $T = 1.1 \times 10^5$ K for the BLA gas and the $T \gtrsim 10^6$ K for the hot corona would result in transition temperatures within the $T = (2.0-3.1) \times 10^5$ K range expected for the O\textsc{vi} gas (see Section 6.2.2).

The low carbon abundance of [C/H] = $-1.5$ dex and $T \sim 10^5$ K suggest that the BLA could be a fragmentation within the hot halo of galaxy G, born out of small-scale density or temperature perturbations. The presence of such condensation clouds in halos are a prediction of certain semi-analytical galaxy formation models (Maller & Bullock 2004). In this scenario, the BLA gas must be a young condensation ($\sim 10^2$ yr) that has not cooled to the typical warm temperatures observed in HVCs. The O\textsc{vi} could in turn be produced at the turbulent layers formed at the boundary between the condensing cloud at $T \sim 10^5$ K and the hot exterior medium described as the galaxy’s corona.

Kinematic displacement between the O\textsc{vi} and the H\textsc{i} could arise if the O\textsc{vi} gas is tracing an evaporative flow within the conductive interface layer (Boehringer & Hartquist 1987; Borkowski et al. 1990). In the context of the LISM, Savage & Lehner (2006) find that significant velocity offsets ($\Delta v \sim 30$ km s$^{-1}$) between O\textsc{vi} absorption and tracers of the warm
of the BLA, and the corresponding upper limits are represented by the dashed lines in these models is set to the value measured for the broad Ly \( \alpha \) line. The H\( \text{I} \) column density for an isochorically cooling gas. The H\( \text{I} \) column density measurement. However, there are two concerns with this possibility. First, theoretical models for a young interface typically predict transition temperatures that are a factor of \( \sim 2 \) higher than the maximum temperature permitted by \( b(\text{O} \text{VI}) \sim 16 \text{ km s}^{-1} \), although these predictions are dependent on model assumptions. Second, the maximum of the velocity offset depends on how steep the temperature gradient is between the separate gas phases that form the interface layer. For the \( z = 0.22638 \) system, the difference in temperature between the BLA and the hot corona may not be sufficient to generate flow velocities which fully account for the measured \( v \sim -50 \text{ km s}^{-1} \) offset between the \( \text{O} \text{VI} \) and \( \text{H} \text{I} \) line centroids.

Another circumstance that can result in a velocity offset is if the BLA and \( \text{O} \text{VI} \) are tracing separate regions of shock heated gas formed when the condensing cloud is moving through a hot low density halo (Quilis & Moore 2001). The collisionally ionized post shock region (gas behind a shock front) can produce \( \text{O} \text{VI} \) at temperatures consistent with the observed line width of \( \text{O} \text{VI} \) (Tumlinson & Fang 2005). The velocity offset between the post-shock region and the shock front will depend on the flow velocity and the geometry of the line of sight through the structure. With only one constraint (the offset velocity), it is difficult to explore such models.

To summarize, the absorber \( z = 0.22638 \) is a multiphase system. The column densities of \( \text{O} \text{VI} \), \( \text{C} \text{II} \) and \( \text{H} \text{I} \) and their line widths suggest that collisional processes control the ionization in the absorber. The BLA is tracing \( T \sim 10^5 \text{ K} \) gas that could be part of a cooling condensing structure within the halo which has not reached temperatures typical of the warm phase of the HVCs. We lack sufficient information to conclude on any unique physical model for the kinematic offset of \( -50 \text{ km s}^{-1} \) between the \( \text{O} \text{VI} \) and BLA gas phases except that the kinematic offset is broadly consistent with the general predictions of conductive interface models as well as shock heated gas.

7. DISCUSSION

Our interpretation of the astrophysical nature of the two absorbers, and the environments they trace, are meaningful in the context of the BLA and its interaction with the surrounding medium. The BLA line width is a factor of \( \sim 0.5 \) lower than the minimum temperature estimated \( T = 1.1 \times 10^5 \text{ K} \) from the Doppler line widths of \( \text{Ly} \alpha \) and \( \text{C} \text{II} \) lines. Even for the model that is approximately consistent with the constraints set by the \( \text{C} \text{II} \) and \( \text{O} \text{VI} \) column densities, the derived model temperature is a factor of \( \sim 2 \) lower than the minimum temperature derived from the line widths. A \( T \sim 10^5 \text{ K} \) cannot be recovered from a gas phase in photoionization equilibrium.
light of some recent results linking O\textsc{vi} absorption to galaxies. From a survey of galaxies in quasar fields with known O\textsc{vi} absorbers, Chen & Mulchaey (2009) found that approximately 90% (10/11) of the absorbing galaxies in their sample are emission line dominated. Those galaxies that are absorption dominated do not have O\textsc{vi} detected down to an equivalent width limit of \(W_r(O\textsc{vi} 1532) \lesssim 0.03 \, \text{Å} \) in the spectrum of the background quasar. Thus O\textsc{vi} seems to be preferentially selecting gas-rich galaxies. The absorbing galaxies were also found to be part of group environments with their morphologies pointing to past events of interactions or satellite accretion. Such interactions were expected to contribute to the \(\sim 64\%\) covering fraction of O\textsc{vi} estimated from their sample. The SFR which we derive from the strength of the H\alpha emission in the spectrum of galaxy G suggests ongoing star formation, consistent with a gas-rich system (see Section 5). It extends the possibility of the \(z = 0.22496\) and \(z = 0.22638\) O\textsc{vi} absorbers tracing gaseous structures which are associated with the extended environments of galaxy G.

Tumlinson et al. (2005) have described the properties of two multiphase O\textsc{vi} absorbers along the line of sight to the low-\(z\) QSO PG 1211 + 143. A galaxy survey of the surrounding field showed that two absorbers are situated within \(150 \, h^{-1} \, \text{kpc}\) of \(L^*\) galaxies. One of those galaxies is part of a spiral-dominated group. The O\textsc{vi} in both those absorption systems are inconsistent with a photoionization origin. The \(b(O\textsc{vi})\) suggests gas temperatures of \(T \gtrsim 10^8 \, \text{K}\). Ion ratios in the two absorbers resemble the highly ionized Galactic HVCs. Tumlinson & Fang (2005) propose that these absorbers are related to the nearby galaxies by outflows or tidal streams created from interactions with unseen satellite galaxies. It is possible for the \(z = 0.22496\) absorber along the H 1821+643 sight line to have an analogous origin. The multicomponent, multiphase absorption profile and the abundance ratio [Si/H] \(\sim -0.6\) dex in the photoionized gas agrees with a description of the absorber tracing tidal debris embedded in the halo of its nearby galaxy G. An extended geometry like that of the Magellanic stream would result in several conductive layers at regions where the high-velocity gas interfaces with the galaxy’s hot corona. The line of sight intercepting such multiple interface layers would explain the significant velocity spread of \(\Delta v \sim 200 \, \text{km s}^{-1}\) in O\textsc{vi} and H\textsc{i} absorption as well as the \(N_0(O\textsc{vi})/N_0(\text{H}^\text{i}) \approx 10^{4.3} \, \text{cm}^{-2}\).

The physical nature of the \(z = 0.22638\) system is relevant for other BLAs with metals detected in the same gas phase. BLAs are characterized by large line widths \(b \gtrsim 40 \, \text{km s}^{-1}\) and shallow absorption \(N(\text{H}^\text{i}) < 10^{14} \, \text{cm}^{-2}\) (Richter et al. 2004, 2006). It is unclear whether the large line width is dominated by thermal or non-thermal effects. Thermal broadening would imply that BLAs are large reservoirs of baryons in the low-\(z\) IGM. Detecting metals in the same phase as the broad Ly\(\alpha\) gas will enable an accurate temperature estimation. For the \(z = 0.22638\) BLA, the \(b(\text{H}^\text{i})\) and \(b(\text{C}^\text{iii})\) imply \(T \sim 1.1 \times 10^5 \, \text{K}\). The temperature indicates the gas to be heavily ionized \((f_{\text{H}^\text{i}} = N(\text{H}^\text{i})/N(\text{H}) \sim 10^{-5})\) with a substantial baryon column density of \(N(\text{H}) \sim 3.2 \times 10^{18} \, \text{cm}^{-2}\).

The \(z = 0.16339\) BLA absorber with \(b(\text{H}^\text{i}) = 46.3 \pm 1.9 \, \text{km s}^{-1}\) detected in the HE 0226−4110 spectrum (Lehner et al. 2006) resembles the \(z = 0.22638\) absorber. In the \(z = 0.16339\) system, there is a marginal (2.9\sigma) C\text{iii} detection that appears shallow and broad, with no associated O\textsc{vi}. The lack of O\textsc{vi} detection points to low metallicity in the gas. If the gas is in CIE at \(T = 1.3 \times 10^5 \, \text{K}\) suggested by the line width of H\text{i}, then the \(N_0(\text{C}^\text{iii})/N_0(\text{H}^\text{i}) \approx 0.01\) ratio yields a carbon abundance of \([\text{C}/\text{H}] \sim -1.8\) dex, an ionization correction of \(f(\text{H}^\text{i}) \sim 9 \times 10^{-6}\) and a \(N(\text{H}) \sim 2.5 \times 10^{19} \, \text{cm}^{-2}\). These values are comparable to the low abundance and the high baryon content for the BLA phase in the \(z = 0.22638\) system. Interestingly, the \(z = 0.16339\) BLA is also coincident in redshift \((z = 0.1630)\) with a relatively bright galaxy \((m_B = 23.74)\) at a projected separation of \(\sim 226 \, h_0^{-1} \, \text{kpc}\) (Chen & Mulchaey 2009). The \(|\Delta v| \sim 117 \, \text{km s}^{-1}\) velocity separation between the absorber and the galaxy favors an origin for the absorption in some high-velocity gas associated with the galaxy. The similarities in derived properties between the \(z = 0.22638\) and \(z = 0.16339\) systems and their proximity to galaxies further emphasizes the likelihood of BLAs with metals in the same gas phase selecting low metallicity high-velocity gas systems in external galaxies. The prospect for detecting such extragalactic absorbers is going to be significantly augmented in the near future with the advent of higher sensitivity observations using the Cosmic Origins Spectrograph.

The \(z = 0.22496\) and \(z = 0.224638\) absorbers being extragalactic HVCs has implications for our understanding of the nature of other O\textsc{vi} absorption systems. In a sample of 51 O\textsc{vi} systems at \(z < 0.5\) identified along 16 sight lines, Tripp et al. (2008) found 53% of the absorbers to be complex multiphase systems with significant velocity offset between the O\textsc{vi} and H\text{i} absorbing components. Even among the fraction of absorbers with closely aligned O\textsc{vi} and H\text{i} components, the temperature implied by the combined line widths of H\text{i} and O\textsc{vi} in 26% of the cases was \(T > 4 \times 10^4 \, \text{K}\). This temperature lower limit is inconsistent with photoionized gas. In such absorbers, nonequilibrium collisional ionization process is a distinct possibility for the production of O\textsc{vi}. O\textsc{vi} could be tracing transition temperature plasma in HVCs embedded within a galaxy halo. The fact that many O\textsc{vi} absorbers are clustered around galaxies further supports this possibility (Wakker & Savage 2009; Chen & Mulchaey 2009).

8. SUMMARY

We have analyzed the properties of \(z = 0.22496\) and \(z = 0.22638\) multiphase absorption systems detected along the sight line to the quasar H 1821+643. The measurements are based on a combination of ultraviolet spectra from Hubble Space Telescope/STIS and FUSE. We also use the existing imaging observations of this quasar field from Savage et al. (1998) for information on galaxies in the vicinity of the absorber. The significant results from our analysis are summarized as follows.

1. The \(z = 0.22496\) and \(z = 0.22638\) O\textsc{vi} absorbers are likely situated within the extended halo of a \(\sim 2L^*\) Scb-Sbc galaxy within an impact parameter of \(\sim 116 \, h_0^{-1} \, \text{kpc}\) from the line of sight. The absorbers are at 158 km s\(^{-1}\) and 191 km s\(^{-1}\) with respect to the systemic redshift of this galaxy. Also coincident in redshift are four other galaxies, at much larger impact parameters, revealing a group environment.

2. The \(z = 0.22496\) system is a multiphase, multicomponent absorber detected in H\text{i}, C\text{ii}, C\text{iii}, C\text{iv}, O\text{iii}, C\text{iv}, and O\text{vi}. C\text{iv} is tentatively detected. Comparison of apparent column density profiles shows that the H\text{i} profile (particularly in higher order Lyman series lines) is better represented by the narrow multicomponent C\text{iii} absorption than by O\text{vi}. The O\text{vi} absorbing components are broader than the components detected in C\text{iii} and C\text{ii}. The kinematics of these components and their line widths suggest that the low/intermediate ions such as C\text{ii}, C\text{iii}, and C\text{iii}
are tracing a lower ionization and cooler gas phase than the phase traced by O VI. This lower ionization gas produces the bulk of the H I absorption.

3. The ionic column density ratios and the measured line widths of C II, Si II, and Si III in the z = 0.22946 absorber are consistent with an origin in a medium that is predominantly photoionized. In this photoionized phase, the N(Si ii)/N(Si iii) = 0.2 in one of the absorbing components yields a density of n_H = 2.5 × 10^3 cm^-3; a total hydrogen column density of N(H) = 3.9 × 10^{17} cm^-2; a photoionization equilibrium temperature of T = 1.3 × 10^4 K, a gas pressure of p/K ≈ 71 cm^-3 K, and a path length of L ≈ 51 pc for the absorbing region. The Si and C abundances in this component are estimated as −0.6 ± 0.4 dex.

4. We find the z = 0.22946 absorber to be analogous to Milky Way highly ionized HVCs detected in low, intermediate, and high ions. Similar to the ionization conditions in highly ionized Galactic HVCs, the low/intermediate ions and bulk of the H I are consistent with having an origin in a warm (T < 5 × 10^4 K) photoionized gas phase, where as the high ions (predominantly O VI) are more likely produced in a collisionally ionized transition temperature plasma (T = (2–3) × 10^5 K). The transition temperature gas is most likely formed at the interface layers between the hot (T ≥ 10^6 K) coronal halo of the galaxy and the warm HVC cloud embedded within it.

5. If the photoionized gas in the z = 0.22946 HVC is confined by the hot halo, then assuming a isothermal halo of T = 2 × 10^6 K, we derive a density of n_H ≈ 10^{-5} cm^{-3} at 100 kpc for the hot halo.

6. The z = 0.22638 system is a multiphase absorber with an offset of v ∼ −50 km s^-1 between the O VI and H I absorption. At the velocity of O VI, we measure N_C/(N(H I)) < 0.2. The O VI line width of b(O VI) = 16 ± 2 km s^-1 implies T ∼ 3 × 10^5 K. The absence of H I and C III absorption at the velocity of O VI is inconsistent with a photoionization origin for O VI.

7. The H I line width in the z = 0.22638 system implies that it is a BLA absorber. Coincident in velocity with the BLA, weak C III is detected, but no O VI. The b(H I) = 51 ± 2 km s^-1 and b(C III) = 28 ± 4 km s^-1 implies T ∼ 1.1 × 10^10 K in this gas phase. At this temperature departures from CIE ionization fractions are significant for certain ions due to metal line cooling. Non-CIE models estimate a carbon elemental abundance of −1.5 dex in the BLA based on the N(C iii)/N(H I) ∼ 0.1 constraint. The BLA represents highly ionized gas (N(H I)/N(H) ∼ 10^{-5} with a total hydrogen column density of N(H) ∼ 3.2 × 10^{18} cm^-2 signifying a large baryon reservoir. This low metallicity BLA could be metal-poor material accreted from the group environment or one of the many cooling fragmentations born out of small-scale thermal instabilities within the hot galactic halo as proposed by Maller & Bullock (2004). It could also be tracing the shock-front of a cloud moving through the halo where the gas is compressed and heated to T ∼ 10^5 K.

8. The collisionally ionized O VI in the z = 0.22638 absorber could be produced in post-shock heated gas trailing behind a low metallicity cloud moving at high velocity (traced by H I and C III) through the halo of galaxy G. Alternatively, it could also be the evaporative gas of a relatively young (< 10^8 yr) conductive interface between the T ∼ 10^5 K BLA and the hot corona of the galaxy. The kinematic offset between the BLA and the O VI are roughly consistent with the general predictions of both these models.

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