COSMIC ORIGINS SPECTROGRAPH OBSERVATIONS OF WARM INTERVENING GAS AT $z \sim 0.325$ TOWARD 3C 263*

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ABSTRACT

We present HST/COS high-S/N observations of the $z = 0.32566$ multiphase absorber toward 3C 263. The Cosmic Origins Spectrograph (COS) data show absorption from H I (Lyα to Lyθ), O vi, C iii, N iii, Si iii, and C ii. The Ne viii in this absorber is detected in the FUSE spectrum along with O iii, O iv, and N iv. The low and intermediate ions are kinematically aligned with each other and H I and display narrow line widths of $b \sim 6–8$ km s$^{-1}$. The O vi λλ1031, 1037 lines are kinematically offset by $\Delta v \sim 12$ km s$^{-1}$ from the low ions and are a factor of $\sim 4$ broader. All metal ions except O vi and Ne viii are consistent with an origin in gas photoionized by the extragalactic background radiation. The bulk of the observed H I is also traced by this photoionized medium. The metallicity in this gas phase is $Z \gtrsim 0.15 Z_\odot$ with carbon having near-solar abundances. The O vi and Ne viii favor an origin in collisionally ionized gas at $T \sim 5.2 \times 10^5$ K. The H I absorption associated with this warm absorber is a broad-Lyα absorber (BLA) marginally detected in the COS spectrum. This warm gas phase has a metallicity of $[X/H] \sim -0.12$ dex, and a total hydrogen column density of $N$(H) $\sim 3 \times 10^{19}$ cm$^{-2}$, which is $\sim 2$ dex higher than what is traced by the photoionized gas. Simultaneous detection of O vi, Ne viii, and BLAs in an absorber can be a strong diagnostic of gas with $T \sim 10^5–10^6$ K corresponding to the warm phase of the warm-hot intergalactic medium or shock-heated gas in the extended halos of galaxies.

Key words: galaxies: halos – intergalactic medium – quasars: absorption lines – quasars: individual (3C 263) – ultraviolet: general

Online-only material: color figures

1. INTRODUCTION

Throughout cosmic history, the intergalactic medium (IGM) and the gaseous envelopes surrounding galaxies have retained more baryons compared to the gas settled into galaxies. In the $z < 0.5$ universe, $>50\%$ of the baryons are predicted to be in the form of low-density ($n_H \sim 10^{-3}$ cm$^{-3}$) intergalactic gas at temperatures of $T \sim 10^5–10^7$ K and moderate overdensities of $\rho/\bar{\rho} \sim 20$. These baryons, which were once part of the cool ($T \lesssim 10^4$ K) photoionized IGM probed by the Lyα forest at $z \gtrsim 3$, were heated through gravitational shocks during the formation of large-scale structures (Cen & Ostriker 1999; Davé et al. 2001; Valageas et al. 2002). The temperatures imply that this warm-hot intergalactic medium (WHIM) gas has a high degree of ionization. Physical conditions similar to the WHIM can also exist in gas in the extended halos of galaxies. Cosmological simulations predict that massive halos ($>10^{12} M_\odot$) acquire most of their gas through the hot-mode of accretion, where the infalling intergalactic gas is shock heated to the virial temperatures of $T \gtrsim 10^6$ K (Kerés et al. 2005; van de Voort et al. 2011). This infalling gas may circulate within the halo for a long time before it can radiatively cool and flow into the disk. Other galactic-scale processes such as supernova-driven flows and tidal interactions/mergers can also increase the temperature and ionization levels of gas in regions close to galaxies.

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Observations of warm gas with $T \sim 10^5–10^6$ K in the low-$z$ universe have been accomplished primarily through quasar absorption line spectroscopy in the far-UV (FUV) of highly ionized metals, particularly O vi λλ1031, 1037 lines (Tripp & Savage 2000; Richter et al. 2004; Danforth & Shull 2005, 2008; Stocke et al. 2006; Tripp et al. 2008) and more recently Ne viii λλ770, 780 (Savage et al. 2005; Narayanan et al. 2009, 2011; Meiring et al. 2012). The fractional abundances of these ions peak in the interval $T \sim (2–7) \times 10^5$ K when ionizations are controlled by ion–electron collisions. Limitations in accessing the FUV wavelengths of the Ne viii resonant transitions and the relatively lower cosmic abundance of neon compared to oxygen have resulted in fewer Ne viii findings compared to O vi. On the other hand, the detection of Ne viii has the advantage that it requires the presence of collisionally ionized warm gas. In the case of O vi it is not straightforward to distinguish a photoionization origin from collisional ionization in warm gas.

A strong correlation between the incidence of O vi absorption and galaxies has been emerging from recent absorber–galaxy surveys. The O vi absorption at low-$z$ seems to be preferentially selecting circumgalactic environments of typical star-forming galaxies (Savage et al. 2002; Fox et al. 2004; Stocke et al. 2006; Wakker & Savage 2009; Tumlinson et al. 2011a; Meiring et al. 2012). The covering fraction of O vi absorbing gas is estimated to be $\gtrsim 65\%$ around emission-line galaxies (Chen & Mulchaey 2009), comparable to the covering fraction of high-velocity O vi around the Milky Way (Sembach et al. 2003). In the case of the Milky Way, the halo O vi absorption is known to be from multiphase high-velocity clouds (HVCs) where the O vi is produced in $T \sim (2–5) \times 10^5$ K transition temperature plasma at the interface layers between the $T \lesssim 10^4$ K neutral...
interstellar gas in HVCs and the \( T \sim 10^6 \) K coronal halo of the Galaxy (Sembach et al. 2003; Fox et al. 2006). As analogs of Galactic HVCs, some fraction of the population of extragalactic warm absorbers could be tracing halo gas associated with galactic-scale processes such as outflows from star formation (Heckman et al. 2001), accretion of WHIM gas from the nearby intergalactic filaments (Narayanan et al. 2010b; Tumlinson et al. 2011b), and/or tidal streams from interactions and mergers with companion galaxies similar to the Magellanic Stream around the Milky Way, with which O \( \text{vi} \) absorption is clearly associated (Sembach et al. 2003).

In the few known Ne \( \text{viii} \) absorbers, associated O \( \text{vi} \) has always been detected, and both ions are found to be tracing the Milky Way, with which O \( \text{vi} \) absorption is clearly associated (Sembach et al. 2003).

This paper adds important FUV Hubble Space Telescope (HST)/Cosmic Origins Spectrograph (COS) data on the \( z = 0.32566 \) Ne \( \text{viii} \) absorber previously detected with \textit{FUSE} data (Narayanan et al. 2009). The detection of Ne \( \text{viii} \) indicated the presence of \( T \sim 10^6 \) K collisionally ionized gas, but the relatively few lines covered in the \textit{FUSE} spectrum (O \( \text{iii} \), O \( \text{iv} \) and N \( \text{iv} \)) were inadequate to constrain the ionization conditions and metallicity in this absorber. The COS spectra are obtained at high S/N and provide coverage of a large number of absorption lines, most importantly O \( \text{vi} \) and H \( \text{i} \). In Sections 2 and 3 we describe the COS observations and \textit{FUSE} observations for this sight line. The line detections and the multiphase properties of the absorber are discussed in detail in Section 4, followed by predictions from photoionization and collisional ionization models in Section 5.

### 2. COS OBSERVATIONS OF 3C 263

COS observations of 3C 263 were carried out as part of the \textit{HST} Cycle 19 GTO Program ID 11541 (PI: J. Green). The capabilities of COS are described in detail by Green et al. (2012) and Froning & Green (2009) and the on-orbit performance of the instrument is discussed by Osterman et al. (2011). The 3C 263 observations consisted of FUV spectra obtained at intermediate resolutions (FWHM \( \sim 17 \) km s\(^{-1}\)) using the G130M and G160M COS gratings with total exposure times of 15.4 ks and 18.0 ks, respectively. The details on the individual exposures are given in Table 1. Different grating central wavelength settings were used for the separate exposures. For different grating central wavelength settings the dispersed light for a particular wavelength falls on a different region of the detector. This helps to reduce the amplitude of detector fixed pattern noise in the final co-added spectrum. The setup also allows for the coverage of the \( \sim 9 \) Å wavelength gap introduced by the separation between the two segments of the COS detector. The data were extracted using the STScI CalCOS v2011.1a pipeline. The separate one-dimensional spectra were co-added in flux units weighted by their respective exposure time using the routine developed by Charles Danforth and the COS GTO team.\(^3\)

### 3. FUSE OBSERVATIONS OF 3C 263

The 3C 263 was observed by \textit{FUSE} (Moos et al. 2000; Sahnow et al. 2000) for a total of 260 ks under various observing programs. The spectra were processed using the CALFUSE (ver 2.4) data reduction pipeline software. \textit{FUSE} covers the wavelength range from 912 Å to 1185 Å sampling the spectrum at a resolution of \( \sim 20 \) km s\(^{-1}\) (FWHM). The S/N of the spectrum at \( \lambda > 1000 \) Å is \( \sim 10–15 \) per 17 km s\(^{-1}\) bin size. The procedures adopted in the co-addition of the spectrum and for correcting the zero-point velocity offset errors are similar to the detailed description given in Walker et al. (2003). More details can be found in Narayanan et al. (2009).

### 4. MULTIPHASE NATURE OF \( z = 0.32566 \) ABSORBER

In Figures 1(a) and (b), we display the \( z = 0.32566 \) centered system plot with prominent metal lines and H \( \text{i} \) detected by both COS and \textit{FUSE}. To be consistent with the previous \textit{FUSE} analysis of this absorber, we adopt the same system redshift as given in Narayanan et al. (2009). The continuum normalization was done by fitting low-order polynomials to the region around each absorption feature. The metal lines with \( > 3 \sigma \) detection by COS for this absorber are C \( \text{ii} \) \( \lambda \lambda 903.96, 903.62, \) C \( \text{ii} \) \( \lambda 1036, \) C \( \text{ii} \) \( \lambda 3777, \) N \( \text{ii} \) \( \lambda 989, \) Si \( \text{ii} \) \( \lambda 1206, \) and O \( \text{ii} \) \( \lambda \lambda 1031, 1037 \). In the system plot we also show non-detections of lines corresponding to N \( \text{ii} \) and Si \( \text{ii} \). In \textit{FUSE}, O \( \text{iii} \) \( \lambda \lambda 382, 4078, \) N \( \text{iv} \) \( \lambda 655, \) and Ne \( \text{vii} \) \( \lambda 770 \) are seen along with a non-detection of O \( \text{ii} \) \( \lambda 834. \)

Measurements on all the lines were carried out using the apparent optical depth (AOD) technique of Savage & Sembach (1991). The AOD measurements on the COS data are listed in Table 2. The column density \( N \), Doppler parameter \( b \), and velocity \( v \) of the line components were also determined through Voigt profile modeling of the lines using the Fitzpatrick & Spitzer (1997) routine. While performing the fits, the model

\(^3\) http://casa.colorado.edu/~danforth/science/cos/costools.html
profiles were convolved with the empirically determined line-spread functions of Kriss (2011) for the redshifted wavelength of each line. The fitting results are given in Table 3 and the profile fits to the absorption lines are displayed in Figure 2.

The COS spectrum shows strong absorption from C iii λ977 with at least two components at velocities of −23 km s\(^{-1}\) and +12 km s\(^{-1}\). Coincident with the positive velocity component are also seen absorption from N iii, Si iii, C ii and H i. For the negative velocity component, these metal ions are non-detections in the COS spectrum down to the 3σ significance level. The difference in the corresponding line strengths between the two components is indicative of ionization or metallicity gradients within the absorber. The C iii λ977 being a strong line \(f_{osc} = 0.762\) is susceptible to saturation unresolved at the FWHM \(\sim 17\) km s\(^{-1}\) of the COS data. Strong saturation will result in the AOD measurements underestimating the column densities in the line cores. We find a difference of \(\sim 0.32\) dex in the column densities between the two measurements. The profile fit to C iii yields a \(b(C\ iii) = 9 \pm 3\) km s\(^{-1}\) for the positive velocity component. The narrower \(b\)-values for C ii and Si iii indicate that the true dispersion in the low-ionization gas could be smaller than what we measure for C iii. Instrumental broadening of narrow spectral lines would result in the column density getting underestimated so as to preserve the equivalent width. Lowering the \(b(C\ iii)\) from its measured value of 9 km s\(^{-1}\) to 6 km s\(^{-1}\) (the 1σ lower limit) yields a column density which

\[\begin{align*}
\text{Figure 1.} & \text{ Continuum-normalized COS and FUSE spectra of 3C263 where } v = 0 \text{ km s}^{-1} \text{ corresponds to } z = 0.32566. \text{ Features which are not part of the absorption system are marked “x” in the corresponding panels. The AOD and profile fit line measurements are listed in Tables 2 and 3. The Ly} \alpha \text{ (H i 950) line is contaminated by Galactic Si ii 1260 and possibly also by S ii 1260. The C ii lines at } \lambda = 903.9616 \text{ Å and 903.6235 Å are labeled as C ii 903a and C ii 903b, respectively. The N iii 1084 and Si iii 1193 transitions covered by COS and O ii 834 transition covered by FUSE are not detected at } \geq 3\sigma \text{ significance.}
\end{align*}\]
is 0.7 dex higher than the free-fit value of 13.67 dex. This shows that the degree of unresolved saturation is significant if the \( b(C\text{iii}) \) is narrower than what we measure. To account for this possibility, we increase the +1\( \sigma \) uncertainty to 0.7 dex in the profile fit \( N \)-value for the positive velocity component of the \( C\text{iii} \) \( \lambda 977 \) line.

The \( \text{Si\text{iii}} \) \( \lambda 1207 \) line is covered by the G160M grating of the COS spectrum. The positive velocity component is very narrow with a measured \( b(\text{Si\text{iii}}) = 5 \pm 3 \text{ km s}^{-1} \). The profile fit column density is \( \sim 0.3 \text{ dex} \) larger than the apparent column density, but within the combined \( \sim 1\sigma \) errors associated with the measurements. At \( v \sim -20 \text{ km s}^{-1} \), weak absorption is detected at \( \sim 4\sigma \) significance which is consistent with being \( \text{Si\text{iii}} \) corresponding to the negative component seen in \( \text{C\text{ii}} \) and \( \text{H}\text{i} \). The \( \text{C\text{ii}} \) multiplet transitions at 903.6235 Å (\( f_{\text{osc}} = 0.168 \)), 903.9616 Å (\( f_{\text{osc}} = 0.336 \)) and 1036.3367 Å (\( f_{\text{osc}} = 0.123 \)) are detected with \( >3\sigma \) significance. In the \( N_\alpha(v) \) comparison in Figure 3, we find that the apparent column density profile of the stronger \( \text{C\text{ii}} \) line is lower than the weaker lines. The \( \text{C\text{ii}} \) line is possibly stronger and narrower than the observed profile but has been blurred by the instrumental spread function. The \( N_\alpha(v) \) integrated column density obtained is therefore only a lower limit. The difference in \( N_\alpha \) values between the weaker \( \text{C\text{ii}} \) \( \lambda 1036 \) and the stronger \( \text{C\text{ii}} \) \( \lambda 903.9616 \) transitions is 0.11 dex. This difference can be used to compensate for the instrumental broadening, as described in Savage & Sembach (1991). The corrected apparent column density measurement of \( \log N_\alpha(\text{C\text{ii}}) = \log N_\alpha(\text{C\text{ii}} 1036) + \Delta \log N_\alpha = 13.29 \pm 0.11 \text{ dex} \) is consistent with the column density obtained from simultaneous profile fitting of the three lines. The \( N_\alpha(v) \) comparison in Figure 3 also shows small excess absorption in the \( \text{C\text{ii}} \) \( \lambda 903.9616 \) line between \( 30 \text{ km s}^{-1} < v < 75 \text{ km s}^{-1} \).
possibly due to line contamination. The separate profile fit on this line yields a larger $b$ value compared to the two weaker CII transitions. We obtain $\log N(C\text{II}) = 13.26 \pm 0.03$ dex and $b(C\text{II}) = 8 \pm 2$ km s$^{-1}$ from simultaneously fitting the three CII lines. A lower $b(C\text{II}) = 6$ km s$^{-1}$ would result in $\log N(C\text{II}) = 13.28$ km s$^{-1}$ which is within the statistical uncertainty in the measurement.

The COS spectrum shows absorption in H I from Lyα to Lyθ. The Lyδ (H I λ9494) line suffers contamination from Galactic Si II λ1260 and possibly also from S II λ1260. The Lyα and Lyβ lines have saturated profiles. The column density and the component structure of H I are best constrained in the higher order Lyman lines with kinematic substructure evident in the H I λ938 and H I λ926 lines. Due to the effect of random noise, the corresponding component structures are not conspicuous in all higher order Lyman lines. We simultaneously fitted the Lyman series lines (except Lyδ which is affected by contamination) by keeping $v$, $b$, and $N$ as free parameters. The best-fit model gave two components of roughly equal strength contributing to the core H I absorption (see Table 3). The $b \approx 17$ km s$^{-1}$ for either component is consistent with temperature for photoionized gas. A comparison of the $N_e(v)$ profiles of H I λ938 and H I λ926 lines with C II λ977 show similar two-component velocity structure (see Figure 3). This kinematic coincidence indicates that the bulk of the H I is contributed by the same gas phase as C II.

The wings of the Lyα profile show the possible presence of a very broad component superimposed on the saturated H I core and spread over the velocity interval $[-v, +v] = [-130, +130]$ km s$^{-1}$. This excess absorption could also be due to the presence of additional narrow kinematic substructures. The resolution of COS is not adequate to rule out this additional complexity in H I kinematics. The total column density of H I obtained from the free fit to the Lyman transitions, however, does not account for this extra absorption in the far wings of the Lyα profile. We discuss more about this possible broad-Lyα feature in Section 5.3.

The O vi is a strong absorption seen in both members of the doublet. The $N_e(v)$ profiles for the O vi λ1031, 1037 lines, shown in Figure 3, are in good agreement with each other suggesting little contamination or unresolved saturation. The doublet lines were simultaneously fitted with a single component. The profiles do not show evidence for any kinematic substructure. The parameters of the profile fit are given in Table 3. The central velocity of the O vi absorption is distinct from the velocities of either component seen in C III or the core absorption in H I. Also, the best-fit $b$ parameter for the O vi line is a factor of $\approx 4$ broader than the C III or H I line widths, which suggests that the two ions are tracing separate gas phases.

In Table 4, we report the equivalent widths and the total apparent column densities for the $> 3\sigma$ transitions seen in the FUSE spectrum. The FUSE spectrum has a factor of $> 3$ lower S/N compared to COS. At the low S/N, the component structure is not evident in the O III λ5303, O IV λ5578, N IV λ678, and Ne vi λ770 lines. The integration range of the $N_e(v)$ profiles for the intermediate ion transitions were therefore broken into two regions of $[-75, -10]$ km s$^{-1}$ and $[-10, 75]$ km s$^{-1}$ to match with the component structure seen in C III, N III, and C II, and H I in the COS spectrum. To compensate for our lack of independent information on the component structure in the low-S/N data, we double the logarithmic errors in the FUSE $N_e$ measurements.
5. IONIZATION MODELING OF THE MULTIPHASE ABSORBER

5.1. Photoionization of the Low and Intermediate Ions

The large difference in the $b$-parameter and the kinematic offset of $|\Delta v| \sim 12$ km s$^{-1}$ between O vi and the low/intermediate metal ions and the H I core points to the presence of multiple ionization phases in the absorber. For modeling the physical conditions in the absorber, we consider the two possible scenarios of ionization by EUV radiation and ionization from ion–electron collisions. The H I and C III lines show absorption in two kinematically distinct components. The column density ratios of the various ions in these two components suggest different ionization conditions in the two clouds. However, constraints are
adequate only for the positive velocity component, and hence we only model that component. Using the photoionization code Cloudy (version C08.00; Ferland et al. (1998)) we solve for the models that best reproduce the observed column density ratios. We have assumed an ionizing background radiation field with contributions from both active galactic nuclei (AGNs) and star-forming galaxies as modeled by Haardt & Madau (2001).

In the positive velocity cloud, the constraint on density comes from the column density ratios of C, N, and O in their adjacent ionization levels, $\log N(C) / N(C)_{\text{III}} \sim -0.41$, $\log N(N) / N(N)_{\text{II}} \sim 0.65$, and $\log N(O) / N(O)_{\text{IV}} \sim 0.15$, along with upper limits of $\log N(N) / N(N)_{\text{III}} \lesssim -0.75$, $\log N(O) / N(O)_{\text{III}} \lesssim -0.20$, and $\log N(S) / N(S)_{\text{III}} \lesssim 0.04$. By fixing the H1 column density in this component to the measured value of $\log N(H) = 15.20$ dex, we ran a series of Cloudy models for a range of ionization parameters. The ion column densities predicted by the photoionization models are shown in Figure 4. The models are consistent with the observed column density ratios within the narrow interval of $-2.6 \leq \log U \leq -2.1$. This corresponds to a density range of $n_H \sim (0.4-2) \times 10^3$ cm$^{-3}$. The single-phase photoionization model which best fits the low and intermediate ions at $\log U \sim -2.2$ predicts $n_H \sim 5 \times 10^3$ cm$^{-3}$, total hydrogen column density of $N(H) \sim 2 \times 10^{18}$ cm$^{-2}$, $T \sim 1.4 \times 10^5$ K, pressure of $p/K \sim 16$ K cm$^{-3}$, and a path length of $\sim 1.6$ kpc through the absorber.

For the given $N(H)$ value, $N(O)$ and $N(OIV)$ are simultaneously predicted at $\log U \sim -2.2$ when the oxygen abundance is $[O/H] = -0.8 \pm 0.1$ dex. The uncertainty comes from the 1σ errors in the column density measurements. To reproduce the other low and intermediate ionic column densities from the same phase, the abundances have to be $[C/H] = 0 \pm 0.04$ dex, $[N/H] = -0.3 \pm 0.1$, and $[Si/H] = -0.6 \pm 0.3$ dex. The higher abundance of carbon is required to explain the observed $N(C)$. The model prediction for $N(C)$ has its peak at $\log U \sim -2.5$ and does not vary much in the interval $-3.2 \leq \log U \leq -1.8$, which sets a robust constraint on the carbon abundance. The estimated abundances are subjected to larger systematic uncertainties at the level of $\sim 0.4$ dex because of ambiguities in the shape and intensity of the ionizing radiation field and assumptions inherent in the Cloudy models.

![Figure 3](https://example.com/figure3.png)

Figure 3. Top panel shows the apparent column density comparison between Cn $904a$ (λ = 903.9616 Å, $f_{osc} = 0.336$), Cn $904b$ (λ = 903.6235 Å, $f_{osc} = 0.168$), and Cn $1036$ (λ = 1035.3367 Å, $f_{osc} = 0.1231$) transitions. The $N(C)$ comparison suggests that the lines are unresolved at the FWHM $\sim 17$ km s$^{-1}$ resolution of COS and are narrower than the observed line widths. The $N(C)$ when corrected for this instrumental blurring is consistent with the profile fit value given in Table 3. In the middle panel we see the kinematic coincidence between the two-component absorption in CII and H1. The component structure in H1 is evident only in the unsaturated higher order Lyman lines. The Cn line aligns with the positive velocity component in CII and H1. The similar $N(C)$ profiles of Ovi 1031, 1037 lines shown in the bottom panel indicates the absence of contamination or unresolved saturation. The Ovi lines are kinematically broader and different compared to CII or Cn.

(A color version of this figure is available in the online journal.)
The most important result from this modeling analysis is that O\textsc{vi} and Ne\textsc{viii} do not occur in the cool ($T \lesssim 10^4$ K) photoionized phase of the absorber. The photoionization model predictions for the O\textsc{vi} column densities are $\lesssim 3$ dex lower than the observed column density. Photoionization of Ne\textsc{viii} requires extremely high ionization parameters of $\log U \sim -0.8$ for even solar [Ne/H] abundances. The corresponding densities of $n_H \sim 10^{-5}$ cm$^{-3}$ lead to very large path lengths ($\gtrsim 1$ Mpc). Absorption over such large path lengths is unlikely to result in the kinematically simple line profiles seen for these high ions. Furthermore, the broadening induced by the Hubble flow on the absorption over such large distances will be at least twice the measured $b$(O\textsc{vi}) = 33 km s$^{-1}$. The photoionization predictions for O\textsc{vi} and Ne\textsc{viii} are thus physically unrealistic. The offset in the velocity centroid of the O\textsc{vi} line and its higher $b$-value in comparison with the low and intermediate ionization species are clear indications of the multiphase gas composition. It is more likely that the O\textsc{vi} and Ne\textsc{viii} are regulated by collisional ionization in a warm plasma at temperatures between $\sim 10^5$--$10^6$ K. We discuss this possibility in the next section.

5.2. Collisional Ionization of O\textsc{vi} and Ne\textsc{viii} in the Warm Gas

We can extract the temperature of the warm phase from the measured column density of O\textsc{vi} (see Figure 5). In the simple collisional ionization models of Gnat & Sternberg (2007) shown in Figure 5, we find that the $N$(Ne\textsc{viii})/$N$(O\textsc{vi}) $\sim 1$ is satisfied for gas temperatures of $T \sim 5.3 \times 10^5$ K. This temperature estimate is independent of the column density of H\textsc{i} in this phase, but assumes a solar ratio for (Ne/O) relative abundances. The temperature corresponds to a thermal line broadening of $b$(O\textsc{vi}) $\sim 23$ km s$^{-1}$, which is consistent with the measured $b$(O\textsc{vi}) = 33 km s$^{-1}$ and indicates roughly equal contributions from thermal and non-thermal line broadening. The $T \sim 5.2 \times 10^5$ K will be a lower limit if we account for the possibility that the O\textsc{vi} can have some contribution from the photoionized gas as well. The intermediate ions like C\textsc{iii}, N\textsc{iii}, O\textsc{iii}, and O\textsc{iv} have very low ionization fractions ($f \lesssim 10^{-5}$) at such temperatures and will contribute negligibly to the total column density.

The H\textsc{i} associated with the warm phase will be broad, dominated by its thermal $b$-value of $\sim 93$ km s$^{-1}$. In other words, it will be a BLA. The very low ionization fraction of $f$(H\textsc{i}) = $N$(H\textsc{i})/$N$(H) $= 5.85 \times 10^{-7}$ would result in the BLA absorption being shallow. This broad component would fall on top of the strong and narrow absorption from the photoionized gas. There is some hint for the presence of such a component in the wings of the Ly$\alpha$ line between velocities of $[-110, -75]$ km s$^{-1}$ and $[+75, +110]$ km s$^{-1}$. The S/N in this region is not adequate to clearly distinguish this feature. Nonetheless, as we show in Figure 6, the observed Ly$\alpha$ profile is consistent with the presence of a broad component with $b$(H\textsc{i}) $= 93$ km s$^{-1}$ and $N$(H\textsc{i}) $\lesssim 13.3$ dex. This upper limit on the BLA column density corresponds to a lower limit of [X/H] $\gtrsim -0.3$ on the true metallicity (see Figure 5). The limiting BLA column density implies a total hydrogen column density of $log N$(H) $\sim 19.5$ dex, a $\sim$2 orders of magnitude higher baryon column density compared to the cool photoionized gas. From this analysis, we conclude a log $N$(H\textsc{i}) = 13.09$(-0.6, +0.3)$ with O and Ne abundances of [X/H] $\sim -0.12$($-0.18, +0.12$) in the warm collisionally ionized phase of the absorber.
5.3. A Constraint on the Broad-Lyα Absorption Tracing the Warm Gas

The metallicity in this warm phase of the absorber is not well constrained since we do not have a direct measure on the associated H\textsc{i}. If the warm gas is spatially coupled with the cooler photoionized gas, we can accept near-solar abundances for O and Ne as well. At solar metallicities and at cooler photoionized gas, we can accept near-solar abundances. At solar metallicities and at cooler photoionized gas, we can accept near-solar abundances. At solar metallicities and at cooler photoionized gas, we can accept near-solar abundances. At solar metallicities and at cooler photoionized gas, we can accept near-solar abundances. At solar metallicities and at cooler photoionized gas, we can accept near-solar abundances. At solar metallicities and at cooler photoionized gas, we can accept near-solar abundances. At solar metallicities and at cooler photoionized gas, we can accept near-solar abundances. At solar metallicities and at cooler photoionized gas, we can accept near-solar abundances.

We applied a formal fit to the Ly\alpha by fixing the two narrow components of the H\textsc{i} core (given in Table 3) and the velocity of the BLA at $v = 0$ km s\(^{-1}\), corresponding to the velocity centroid of the O \textsc{vi} doublet lines. The fit yields a $b(H\textsc{i}) = 86 \pm 6$ km s\(^{-1}\) and $log[N(H\textsc{i})] = 13.25 \pm 0.17$ dex. Considering the low detection significance of the BLA, the fitting procedure has underestimated the errors. The derived fit parameters are sensitive to the choice of the continuum and the assumptions on the component structure made on the basis of profile fitting. Regardless of this, it is interesting to note that the $b$ from the best-fit model is comparable to the value expected for $b(H\textsc{i})$ from gas at $T \sim 5.2 \times 10^5$ K.

6. SUMMARY

We have added new insights into the gas-phase properties of the $z = 0.32566$ Ne \textsc{viii} absorber with the help of HST/COS high-S/N spectroscopic observations of 3C 263. The FUSE detection of Ne \textsc{viii} was reported by Narayanan et al. (2009). The COS spectrum with coverage over the wavelength range of 1136–1796 Å shows lines from H\textsc{i} (Ly\alpha to \theta), O \textsc{vi}, C \textsc{iii}, Ne \textsc{viii}, and C \textsc{ii} at $z = 0.32566$, in addition to useful upper limits from non-detections of N \textsc{ii} and Si \textsc{ii}. This is supplemented by archival FUSE observations of O \textsc{iii}, O \textsc{vi}, N \textsc{v}, and Ne \textsc{viii}.

The main conclusion is that the Ne \textsc{viii} combined with O \textsc{vi} and possible broad H\textsc{i} in this absorber are diagnostic of collisionally ionized gas with $T \sim 5.3 \times 10^5$ K. The other significant results are summarized as follows.

1. The $z = 0.32566$ absorber is a multiphase mix of low-ionization gas at $T \lesssim 10^4$ K and warm high-ionization gas at $75 \times 10^5$ K. Absorption in the low-ionization gas shows at least two components at $v \sim -23$ km s\(^{-1}\) and $+12$ km s\(^{-1}\) in the higher order Lyman lines and in the C \textsc{iii} $\lambda 9771$ line. The COS spectrum also shows N \textsc{iii}, Si \textsc{iii}, and C \textsc{ii} associated with the positive velocity component. The $b$-values of these intermediate and low ions are $\lesssim 10$ km s\(^{-1}\) implying low temperatures. The O \textsc{vi} $\lambda \lambda 1031, 1037$ lines are a factor of $\sim 4$ broader and are not kinematically aligned with the low, intermediate ions or the core of the H\textsc{i} profile.

2. The low and intermediate ions are consistent with an origin in gas photoionized by the extragalactic background radiation. The bulk of the observed H\textsc{i} is also traced by this photoionized medium. Simple photoionization models predict the measured low and intermediate ion column densities for a log $U \sim -2.2$ corresponding to a density of $n_\text{H} \sim 5 \times 10^{-4}$ cm\(^{-3}\), and a total hydrogen column density of $N(H) \sim 2 \times 10^{18}$ cm\(^{-2}\). The abundances in the photoionized phase are $[C/H] = 0 \pm 0.04$ dex, $[N/H] = -0.3 \pm 0.1$, $[O/H] = -0.8 \pm 0.1$ dex, and $[Si/H] = -0.6 \pm 0.3$ dex.

3. The O \textsc{vi} and Ne \textsc{viii} favor an origin in collisionally ionized gas. The $N(O \textsc{vi}) \sim N(Ne \textsc{viii})$ is predicted at $T = 5.2 \times 10^5$ K in CIE and non-equilibrium cooling models. The H\textsc{i} absorption associated with this warm absorber is a BLA with $b(H\textsc{i}) \sim 93$ km s\(^{-1}\) and comes from the trace neutral fraction ($f(H\textsc{i}) = N(H\textsc{i})/N(H) = 5.85 \times 10^{-7}$) of hydrogen. The BLA is only marginally detected in the COS spectrum. From the observed Ne \textsc{viii}, O \textsc{vi}, and the constraints set by the Ly\alpha profile, we estimate for the warm
Figure 6. Top panel shows the Lyα line in the $z = 0.32566$ absorber with the profile model (blue) superimposed. The model was obtained by simultaneously fitting Lyα and six higher-order Lyman series lines in the COS spectrum. The best-fit model has two components of approximately equal to $N$ and $b$-values at $v = −28 \pm 4$ km s$^{-1}$ and $v = 7 \pm 3$ km s$^{-1}$. The location of these components is marked by the vertical ticks. The fit parameters are given in Table 3. In the middle and bottom panels are shown the cumulative Lyα profile obtained when a BLA of $b$(H$\alpha$) = 93 km s$^{-1}$ and log$[N$(H$\alpha$)$] = 13.0$ dex and 13.3 dex, respectively, is added to the absorption at $v = 0$ km s$^{-1}$. The BLN profile is shown by the red curve. The width of the BLA is set by the temperature derived for the measured $N$(Ne vi)/$N$(O vi) from collisional ionization models. From the cumulative three component model, we can constrain log$[N$(H$\alpha$)$] ~ 13.2$ dex in the BLA.

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

gas phase a metallicity of $[X/H] \sim −0.12(−0.18, +0.12)$, and a total hydrogen column density of $N$(H$\alpha$) = $3 \times 10^{19}$ cm$^{-2}$. The warm absorber contains a factor of $~2$ dex more baryons than what is traced by the photoionized gas.

The ionization properties of the warm gas in this absorber are consistent with those predicted for the warm component of the WHIM, although the near-solar chemical abundances for carbon are higher than what is expected for the IGM. The absorber could be kinematically associated with halo gas. Without deep galaxy redshift measurements for the field surrounding 3C 263, it will be difficult to draw firm conclusions about the actual physical site of the absorption. In Table 5, we have summarized the properties of the currently known population of O vi–Ne vii absorbers. Except for the sight line discussed in this paper, imaging data exist for all the other fields. In four out of the six remaining instances, relatively bright galaxies (0.01−1$L^*$) were found proximate (∼200 kpc) to the absorbers. This is consistent with the correlation of O vi absorbers with galaxies (e.g., Wakker & Savage 2009), particularly their higher covering fractions around galaxies that show evidence for star formation (Chen & Mulchaey 2009; Tumlinson et al. 2011a).

We note that there have been few detections of Ne vii–O vi absorbers tracing $T \sim (0.5−1) \times 10^6$ K gas. One would expect an occasional imprint of the hot component of the WHIM in quasar spectra by way of absorbers with $N$(Ne vii) > $N$(O vi) (see Figure 6). The apparent dearth of $T \sim 10^6$ K Ne vii systems is puzzling, although the current statistics are small. A straightforward interpretation is that the Ne vii absorbers in the current sample are having a physical origin different from the filamentary structures of the WHIM outside the virial boundaries of galaxies. The near-solar abundances are consistent with their origin in the extended regions around galaxies. Galaxy simulations find that the inclusion of feedback from star formation and AGNs can heat circumgalactic gas to the warm temperatures of the WHIM (Cen & Ostriker 2006; Tepper-García et al. 2012). In the simulations by Tepper-García et al. (2011), the majority of halo O vi absorbers are tracing such high-metallicity regions enriched by supernova-driven outflows where the gas has started to radiatively cool from the post-shock temperatures of $T \gtrsim 10^6$ K.

The multiphase mix of cool and warm gas phases found in the Ne vii–O vi absorbers are also analogs to the highly ionized Milky Way HVCs. The Ne vii could have an origin similar to O vi in the interface layers between the $T \lesssim 10^4$ K high-velocity gas and the $T \gtrsim 10^6$ K coronal ISM surrounding the galaxies (Sembach et al. 2003; Fox et al. 2004, 2006). The properties of several extragalactic O vi absorbers are found to be consistent with ionization in such conductive interfaces or mixing layers (Narayanan et al. 2010a; Savage et al. 2010, 2011; Tumlinson et al. 2011b; Tripp et al. 2011). The transition temperatures at the layers between the cold and hot phases would explain the narrow range in temperature probed by the current sample of Ne viii absorbers (see Table 5).

The high-sensitivity spectra afforded by COS will possibly reveal many more Ne vii–O vii warm absorbers in the low-redshift universe. Understanding where those absorbers reside with respect to galaxies along with a measurement on their chemical abundances will be important while predicting the origin of the warm gas. High metallicities and proximity to galaxies would favor an origin for the Ne vii and O vii in virialized halos rather than the canonical WHIM distant from galaxies.

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Table 5
Properties of Known O\textsc{vi}–Ne\textsc{vii} Intervening Absorbers

| QSO          | z     | log N(O\textsc{vi}) | log N(Ne\textsc{vii}) | log T  | log N(H) | [X/H] | Assoc. Galaxy | Note |
|--------------|-------|---------------------|-----------------------|--------|----------|-------|---------------|------|
| HE 0226-4110 | 0.2070| 14.37 ± 0.03        | 13.89 ± 0.11          | 5.70   | ~ 20.1   | ~ − 0.9 | 109 kpc, 0.25 L* | 1    |
| PKS 0405-123 | 0.4951| 14.39 ± 0.01        | 13.96 ± 0.06          | 5.72   | ~ 19.7   | ~ − 0.6 | 110 kpc, 0.08 L* | 2    |
| PG 1148+549  | 0.6838| 14.47 ± 0.03        | 13.98 ± 0.09          | 5.68   | ~ 19.8   | > − 0.5 | ...            | 3    |
|              | 0.7015| 14.29 ± 0.04        | 13.75 ± 0.07          | 5.69   | ~ 19.2   | > 0     | ...            | 3    |
|              | 0.7248| 13.84 ± 0.10        | 13.70 ± 0.12          | 5.72   | ~ 18.8   | > 0     | 217 kpc, L*    | 3    |
| 3C 265       | 0.3257| 13.98 ± 0.05        | 13.99 ± 0.11          | 5.72   | ~ 19.3   | > − 0.1 | ...            | 4    |
| PG 1206+459  | ~0.927| ...                 | ~14.90                | ~5.67  | ~ 19.8   | > 0     | 68 kpc, 1.8 L* | 5    |

Notes. (1) From Savage et al. (2011); the abundance list is for oxygen. (2) From Narayanan et al. (2011); the abundance list is for neon; the total hydrogen column density was found to be in the range 19–20 dex. (3) The z = 0.6838 and z = 0.7015 absorbers in Meiring et al. (2012) have no associated galaxies detected down to $m_U < 27$. (4) This paper; there is no galaxy information available for this sight line. (5) The absorption has several components kinematically spread over ~1450 km s$^{-1}$. The Ne\textsc{vii} column density listed is the total column density from all the components as given in Tripp et al. (2011). The temperature, metallicity, and information on the galaxy are based on Tripp et al. (2011). The O\textsc{vi} lines are covered only in the lower resolution (FWHM ~ 230 km s$^{-1}$) HST/FOS spectrum and reported in Ding et al. (2003). The absorption is very strong [$W(\text{O}\textsc{vi} 1032) \sim 0.5 \AA$], but there are no column density measurements because of various line contamination issues.

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