A High Signal-to-Noise HST Spectrum Toward J1009+0713: Precise Absorption Measurements in the CGM of Two Galaxies

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ABSTRACT

High signal-to-noise spectra toward background quasars are crucial for uncovering weak absorption that traces warm gas, such as N V or broad Ly-α lines, in the circumgalactic medium (CGM) of intervening galaxies. We present a new, high signal-to-noise spectrum from the Hubble Space Telescope toward the quasar SDSS J1009+0713 and analyze absorption systems in the CGM of two galaxies close to the line of sight. We identify additional absorption in the CGM of these galaxies that was not reported by the previous low signal-to-noise spectrum, as well as additional Milky Way absorbers and quasar outflows from J1009+0713. We measure log(N_NV/N_OVI) ~ −1 for two CGM absorbers, inconsistent with collisional ionization equilibrium and consistent with a radiatively cooling bulk flow of ~ 30 − 80 km s⁻¹, which could be produced by post-shock galactic winds. These column density ratios are also consistent with those found for other galaxies in the COS-Halos sample and for gas in the Milky Way’s halo. We place upper limits of log(N_NV/N_OVI) < −1 for other O VI absorbers in the same halos, which suggests that O VI is ionized by different ionization processes within the same galactic halo. Together with the kinematically different structure of high- and low-ionization lines, these results indicate there are many components to a single galaxy’s gaseous halo. We also find the redshift number density of Ly-α forest absorbers and broad Ly-α absorbers in the full spectrum are consistent with expectations at this redshift.

Key words: galaxies: haloes

1 INTRODUCTION

The circumgalactic medium (CGM), the expanse of gas that fills a galaxy’s halo outside of the galactic disk and inside the virial radius of the dark matter halo, is crucial for regulating gas flows into and out of the galaxy and as such is directly linked to galactic evolution. Measuring the density, temperature, total mass, and metallicity of gas in a galaxy’s CGM is important for classifying it as inflowing or outflowing and for predicting its origin, fate, and relation to galaxy properties (for a review, see Tumlinson et al. 2017).

The extended CGM, far from the galaxy, is too diffuse to be easily measured in emission in the ultraviolet (UV) and instead, UV CGM surveys focus on detecting CGM gas in absorption. In the X-ray band, the CGM is detected in both absorption and emission (e.g., Gupta et al. 2012, 2014 and references therein). “Down the barrel” studies (Heckman et al. 2000; Steidel et al. 2010; Bordoloi et al. 2011; Martin et al. 2012; Rubin et al. 2014; Chisholm et al. 2018) measure absorption against the starlight of the galaxy itself and typically probe the inner CGM. Quasar absorption line studies (Rudie et al. 2012; Tumlinson et al. 2013; Bordoloi et al. 2014; Keeney et al. 2017) use spectra of quasars that lie behind a galaxy of interest at some impact parameter to analyze absorption of the foreground galaxy’s CGM gas in the quasar spectrum. The Cosmic Origins Spectrograph (COS) on the Hubble Space Telescope has enabled large surveys of CGM gas surrounding several different types of galaxies.
such as low-redshift \( L^\star \) galaxies (COS-Halos; Tumlinson et al. 2011) and COS-GASS; Borthakur et al. 2013), starbursting galaxies (COS-Burst; Heckman et al. 2017), galaxies with active galactic nuclei (COS-AGN; Berg et al. 2018), luminous red galaxies (COS-LRG; Chen et al. 2018), and dwarf galaxies (COS-Dwarfs; Bordoloi et al. 2014). These surveys provide statistical trends of the CGM surrounding many types of galaxies, as functions of galaxy mass, halo mass, and impact parameter.

While useful for deducing typical properties of the CGM, many COS surveys are shallow and broad, focusing on obtaining as many spectra as possible with low signal-to-noise. Low, intermediate, and high ionization state metal lines are observed in the CGM, indicating the CGM is multiphase and ionization modeling is non-trivial. High signal-to-noise spectra probing the CGM are necessary to obtain precise measurements of column densities and absorption line kinematics that promote detailed ionization modeling of the CGM gas. In addition to the increase in precision granted by higher signal-to-noise, deeper spectra may also identify weak lines that shallow spectra cannot: N V, an ion that provides insights to the ionization process of warm gas, and broad Ly-\( \alpha \) absorbers (BLAs), which indicate H I gas at a high temperature (Richter et al. 2006; Tepper-Garcia et al. 2012).

In particular, the high-ionization state metal lines N V and O VI have a number of processes that could ionize them: collisional ionization equilibrium (CIE), photoionization equilibrium, non-equilibrium cooling flows, turbulent mixing, AGN proximity zone fossils (Segers et al. 2017), or hot gas shocking cold clouds (Indebetouw & Shull 2004; Wakker et al. 2012; Bordoloi et al. 2017). Precise measurements of the O VI and N V column densities help discriminate between the various ionization processes to determine where the high-ionization state metals originate and what phase of gas they trace. Because there are so many processes to distinguish between, with possibly multiple processes occurring within the same halo, ionization modeling is better performed in an accurately-measured single system than in a broad and shallow survey.

In this paper, we present a high signal-to-noise spectrum toward the quasar SDSS J1009+0713. This quasar, at a redshift of \( z = 0.456 \), illuminates the CGM of two foreground galaxies at redshifts \( z = 0.228 \) and \( z = 0.356 \) at impact parameters of 60 and 44 kpc, respectively. We describe the reduction and normalization of the spectrum and present the full spectrum with all identified absorption lines in [2] then compare absorption lines at the two galaxy redshifts with previous, shallower spectra from the COS-Halos survey in [3]. We fit all detected absorption lines at the two galaxy redshifts and report column densities, velocity offsets of absorption from each galaxy’s systemic velocity, Doppler broadening parameters, and improvements to measurements over the previous spectrum of this object in the COS-Halos survey in [3]. Section 4 presents an estimate of the ionization processes most likely to produce the low- and high-ionization absorption [4] and specifically the detected N V and O VI absorption [5, 2], and a comparison to other measured CGM N V to O VI column density ratios [1, 2]. Finally, we find that the number of Ly-\( \alpha \) absorbers in the spectrum matches the expected number of Ly-\( \alpha \) absorbers for the covered redshift range in [1, 3] and identify which of those are broad Ly-\( \alpha \) absorbers in [1, 4]. We summarize and conclude in [5].

2 THE SPECTRUM

The quasar SDSS J1009+0713 was chosen for this study because it is bright, making a high signal-to-noise spectrum easier to obtain, and because the two galaxies’ CGM it probes were previously measured to have high O VI column densities, indicating the presence of substantial warm-hot gas. The previously obtained data are also useful for determining the degree of improvement a deeper spectrum can provide. The Hubble Space Telescope observed SDSS J1009+0713 for 21 orbits, a total exposure time of 69569 seconds (\( \approx 1159 \) minutes), using the Cosmic Origins Spectrograph (COS) 160M grating. Half of the exposure time used the 1577 Å central wavelength of the grating and the other half used the 1600 Å central wavelength, to cover the gap in detector segments. The COS spectroscopic exposure time calculator estimates a (wavelength-dependent) signal-to-noise ratio per resolution element of 25 – 30, much higher than the previously obtained spectrum of this object in the COS-Halos survey (Tumlinson et al. 2013), which had a signal-to-noise ratio of \( \approx 7 – 15 \) per resolution element. On the wavelength range investigated, the spectral resolution, measured as the FWHM of the line spread function, is \( \approx 0.1 \) Å. The data were reduced and combined into a single spectrum using the standard CALCOS pipeline. The continuum flux of the target in the range of the spectrum from \( \sim 1380 \) Å to \( \sim 1775 \) Å is \( \sim 3.5 \times 10^{-15} \) ergs s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\), and the typical error on the flux is \( \sim 3 \times 10^{-16} \) ergs s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\) at the continuum level, dropping to \( 1 \times 10^{-16} \) ergs s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\) in absorption features.

We normalize the spectrum using an automatic, iterative process. In essence, we first smooth the spectrum over a large number of pixels (on the order of 600). Then, we subdivide the spectrum into small bins of 30 – 40 pixels, the midpoints of which serve as fulcrums for a spline-fitting of a third order polynomial. In the first iteration, the median of all pixels within each bin is taken as fiducial value for the estimate of the continuum. We then reject in each bin pixels that lie below the spline fit by more than \( 2 \sigma \), thereby eliminating most areas that are affected by absorption, and subsequently recalculate the median for the remaining pixels, thus producing a new estimate. This process is iterated until the change in the resulting continuum estimate falls below the 3\% margin for all remaining pixels. For more details of this procedure see e.g. Pieri et al. (2014) and Frank et al. (2018), both of which have employed the same method. Figure 1 shows the unnormalized spectrum in the top panel and the normalized spectrum in the bottom panel. Also plotted in the top panel is the continuum estimation as a cyan curve.

The full, normalized spectrum is plotted in 25-Å segments in Figures 2–4. We identify the wavelength of potential absorption lines using the atomic data provided with the VPFit\(^1\) program, most of which was compiled in

\(^1\) R. F. Carswell & J. K. Webb, https://www.ast.cam.ac.uk/ rfc/VPFit.html
Figure 1. Top: The full, unnormalized spectrum. The cyan curve shows the best-fit continuum curve. Bottom: The normalized spectrum, after dividing by the cyan continuum curve in the top panel.

Morton (2003), and the redshift of the two galaxies of interest (as determined by Werk et al. 2012), as well as the redshift of the quasar and the Milky Way (z = 0). We restrict the potential absorption lines to various ionization states of elements commonly observed in UV absorption: H, C, N, O, S, Si, and Fe. The most prominent lines of other elements, such as Ar, Ni, P, Mg, or Mn, are either not covered by our spectrum or do not show any absorption at the redshifts of either galaxy, the quasar, or the Milky Way, so they are not plotted in Figures 2-6. There are many absorption lines that are not identified in this way, which we assume to be hydrogen absorption due to the Ly-α forest (see §4.3) at low redshift.

In addition to identifying absorption at or near atomic transitions, we search for absorption blue-shifted from the quasar’s redshift, indicative of quasar outflows. We identified the repeating, multi-component structure at ~1497–1502 Å and ~1505–1510 Å as highly-blueshifted O VI λ1031 and O VI λ1037 absorption from the quasar’s outflow, which corresponds to velocities of ~100–1300 km s^{-1}. Using the extent of the O VI λ1031 absorption as indicative of the velocities over which we could expect to see absorption from the quasar’s outflow, we searched for other absorption systems at these velocity blue-shifts from the quasar’s redshift. Other quasar outflow absorption lines we find are C III λ977 at ~1419 Å and ~1421 Å. The regions of quasar outflow absorption are marked in Figures 2-6 as horizontal cyan lines extending over the full range of the O VI λ1031 absorption, and labeled as “outflow.”

2.1 Absorption Lines

Table 1 lists the equivalent widths of all lines we identify as belonging to the Milky Way (MW), the quasar (QSO), or the combination of several lines from the MW, QSO, or either galaxy that may be too blended to disentangle and fit. We also include lines that are highly-blueshifted absorption from the quasar outflow and the range of velocities over which absorption occurs. Table 1 lists only those lines that we identify but do not fit, Table 2 lists all absorbing systems that we cannot identify, and Tables 3 and 4 list lines that we identify as arising from the CGM of the two galaxies and which we fit. We assume the unidentified absorption lines presented in Table 2 are due to the Ly-α forest (see §4.3), and refer to these lines as Ly-α absorbers throughout the rest of the paper.

We consider an identified absorption system to be blended or contaminated by another when the absorption component structure of one part of a doublet does not match that of the other. In all such cases, we take the weakest absorption structure to be non-contaminated and the other, non-matching absorption structure to be contaminated. For certain contaminated lines, it is clear that another absorption line nearby is responsible for blending, but not all contaminated systems have nearby identified lines. In those cases, we assume the blending is due to absorption in the Ly-α forest, but do not list these absorption features in Table 2 because the fit becomes uncertain when the absorption from a different ion must first be subtracted out.

2.1.1 Galaxy 1 at z = 0.22784

The first galaxy is located 59 kpc from the quasar sightline at a redshift of z = 0.22784, measured from the Keck LRIS optical spectra taken as part of the COS-Halos program (Werk et al. 2012). It has a stellar mass of 10^{9.85} M_⊙ and a star formation rate of 4–9 M_⊙ yr^{-1}, depending on whether it was measured from the Balmer emission lines or [O II], with the [O II]-measured star formation rate being higher.
Common CGM absorption lines covered by our spectrum for the first galaxy are H I $\lambda$1215 Å, C II $\lambda$1334 Å, N V $\lambda$1238,1242 Å, Si II $\lambda$1190,1193,1260 Å, Si III $\lambda$1206 Å, and Si IV $\lambda$1393,1402 Å. Of these, COS-Halos had previously identified C II $\lambda$1334 Å and Si III $\lambda$1206 Å. The COS-Halos spectrum also covers O VI $\lambda$1031,1037 Å whereas our spectrum does not, so we include these lines in our analysis. Note, however, that the COS-Halos spectrum has a much lower signal-to-noise ratio than the new spectrum reported here, so any best-fit parameters we derive from it have significantly larger errors than the fits to absorption in the new spectrum. Figure 7 shows these absorption lines as a function of velocity. A $v = 0 \text{ km s}^{-1}$ indicates that the absorption is at the same redshift as the galaxy, without any additional line-of-sight motions, and negative velocities indicate blueshift.

The Si II transitions show absorption at $\sim -50 \text{ km s}^{-1}$. The higher ionization states of Si that we detect also show absorption at $\sim -50 \text{ km s}^{-1}$, but Si III A1206 Å and Si IV $\lambda$1393,1402 Å also show some weak absorption at $v = 0 \text{ km s}^{-1}$. C II $\lambda$1334 Å also shows an absorption component at $v = -50 \text{ km s}^{-1}$. The absorption detected in many lines...
of varying ionization energies, i.e. Si II and C II, Si III, and Si IV at $-50$ km s$^{-1}$ may indicate multiphase gas in photoionization equilibrium that is comoving in the CGM of this galaxy.

The N V absorption is contaminated at $\lambda 1238$ Å, so we use only the $\lambda 1242$ Å half of the doublet to trace N V. The absorption is weak and centered at $\sim -30$ km s$^{-1}$, which does not align with any of the absorption components seen in the low ions. However, compared to the O VI absorption in the COS-Halos spectrum (which we measure only from the $\lambda 1031$ Å half of the doublet due to contamination at $\lambda 1037$ Å), the N V absorption aligns with the negative-velocity component of the O VI absorption. These ions are the highest ionization states we detect in the CGM of this galaxy and they do not align in velocity space with the other, lower ionization state lines we detect. The different velocities and kinematic structure of low- and high-ionization state lines show they trace separate components of the CGM.

H I is fully saturated in absorption from $-100$ km s$^{-1}$ to 75 km s$^{-1}$, and shows three other, weaker components at $\sim -275$ km s$^{-1}$, $\sim 115$ km s$^{-1}$, and $\sim 215$ km s$^{-1}$. The weaker H I component at $\sim 115$ km s$^{-1}$ aligns well with one of the O VI absorption components and one of the Si III absorption components, but we do not detect absorption at this velocity in any other ion. There is a large spread of ionization energies in which the $\sim 115$ km s$^{-1}$ component is detected, which may indicate that this component represents comoving multiphase gas. We do not detect any metal absorption line components outside of the velocity range of
H I absorption. These might be similar to the high-velocity clouds (HVCs) of our own MW (Sembach et al. 2003).

2.1.2 Galaxy 2 at $z = 0.35569$

Galaxy 2 is located 43 kpc from the quasar sightline, at a redshift of $z = 0.35569$, and has a stellar mass of $10^{10.24} M_\odot$ and a star formation rate of $2 - 3 M_\odot$ yr$^{-1}$, measured from both the Balmer emission lines and [O II] emission (Werk et al. 2012).

The absorption lines we identify in the CGM of the second galaxy at $z = 0.35569$ are H I $\lambda 1215, \lambda 1025$ Å, N II $\lambda 1084$ Å, N V $\lambda 1238, \lambda 1242$ Å, O I $\lambda 1302$ Å, O VI $\lambda 1031, \lambda 1037$ Å, Si II $\lambda 1190, \lambda 1193, \lambda 1260, \lambda 1304$ Å, and Si III $\lambda 1206$ Å. Of these, COS-Halos had previously identified N II $\lambda 1084$ Å, O I $\lambda 1302$ Å, O VI $\lambda 1031$ Å, Si II $\lambda 1260$ Å, and Si III $\lambda 1206$ Å. Figure 4 shows these absorption lines in the normalized spectrum, as a function of velocity relative to the galaxy’s systemic velocity.

The four Si II transitions show a multicomponent structure, with absorption features at $\sim -85$ km s$^{-1}$, $\sim 10$ km s$^{-1}$, and $\sim 90$ km s$^{-1}$. There is significant contamination of the $\lambda 1190, \lambda 1304$ Å transitions of this ion, so we consider only the $\lambda 1193, \lambda 1260$ Å transitions as representative of the Si II absorption. The Si III absorption is saturated for velocities $-20$ to $100$ km s$^{-1}$, but has an additional weaker component at $-85$ km s$^{-1}$ that aligns with the velocity of one of the prominent Si II absorption components. Because the saturated Si III absorption occupies the same velocity space as the other two prominent Si II absorption components, it...
is possible that the saturated absorption is formed by the combination of these two strong absorption components. Si III shows an additional weak absorption component at 200 km s$^{-1}$. N II and O I show absorption that align with two of the three Si (both Si II and Si III) absorption components, at $\sim 10$ km s$^{-1}$ and $\sim 90$ km s$^{-1}$.

O VI is strongly absorbed and spread out in velocity space, with absorption from $-150$ to $250$ km s$^{-1}$. The O VI $\lambda$1037 Å transition is contaminated, so we consider only the $\lambda$1031 Å transition to be representative of the O VI absorption. It is unclear how many absorption components make up the full range of O VI absorption, but there is clearly a strong and broad absorption component at $-85$ km s$^{-1}$ that aligns well with absorption components in all Si lines. O VI also shows a clear absorption component at $\sim 200$ km s$^{-1}$, which aligns with the weakest absorption component in Si III, indicating that the gas this component traces may be multiphase, if the intermediate and high ions are not just comoving but also cospatial. We detect a single, weak N V absorption line at $\sim -100$ km s$^{-1}$, which aligns with the most negative velocity absorption component in O VI, Si II, and Si III, but does not align with any absorption in O I or N II. Some components of the O VI absorption align in velocity with the low-ionization state lines, but the overall kinematic structure of this high-ionization state line is drastically different than that of the low-ionization state lines. Like galaxy 1, the high- and low-ions trace different gas phases that track separate components of the CGM.

Like for galaxy 1, H I here is saturated and spread in velocity space from $\sim -150$ to $\sim 250$ km s$^{-1}$, which encom-
passes the full range of absorption velocities of the metal ions. H I λ1025 Å has a non-saturated absorbing component at \( \sim 200 \text{ km s}^{-1} \), which aligns well with the most positive velocity absorbing components in both O VI and Si III, but is not seen in the other, lower-ionization state lines N II, O I, or Si II. This component may be high-temperature gas that is highly-ionized and also produces fairly broad H I absorption at a comoving velocity, but does not contain any lower-temperature gas hosting low-ionization state species. We defer more detailed ionization modeling to a future paper.

### 2.2 Newly-Identified Absorption

Due to the high signal-to-noise ratio of our spectrum, we have identified new absorption components that were not previously identified in the COS-Halos study of this spectrum. For both galaxies, the most important new discovery is the N V absorption, as this high ion is a useful diagnostic of the ionization processes of the gas traced by high ions, especially when combined with O VI (see §4.2). N V is very weakly absorbed in the CGM and high signal-to-noise spectra like the one presented here are necessary to detect it. In addition to discovering new ions, a deep spectrum can reveal new, weak components of other ions so that a more complete picture of the CGM can be developed including more...
than just the majority of the gas traced by the strongest absorbers.

### 2.2.1 Galaxy 1 at z = 0.22784

The only absorption lines identified by both the previous COS-Halos spectrum and our spectrum for galaxy 1 are H I λ1215 Å, C II λ1036 Å and Si III λ1206 Å. We identify the same absorption components for these two metal ions as COS-Halos, but we find an additional, weak component of Si III absorption at ~115 km s⁻¹ that was not detected by COS-Halos. The Si II and N V lines that we identify are too weak to be detected in the COS-Halos spectrum, although the spectrum does cover their wavelengths. Our spectrum does not reach the wavelengths of the O VI transitions for this galaxy, but the COS-Halos spectrum does. In §4.4, we will use the O VI absorption from the COS-Halos spectrum together with the N V absorption from our spectrum to constrain the column density ratio of these two ions, but we caution that the significantly lower signal-to-noise ratio of the COS-Halos spectrum than our spectrum puts large errors on this ratio.

### 2.2.2 Galaxy 2 at z = 0.35569

For the ions detected in absorption by COS-Halos, we do not detect any additional absorption features that they do not report. However, our higher signal-to-noise spectrum allows for a cleaner decomposition of absorption into components. For example, our detected absorption in O VI is spread over a similar velocity range as determined by Tumlinson et al. (2011), but the most negative and most positive velocity absorption components are clearer and easier to centroid. The same is true of our Si II and N II lines. We report a weak detection of N V absorption that was not seen in the COS-Halos spectrum, due to being weaker than the detection limit. We also report absorption in more transitions of Si II than COS-Halos reported.

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**Table 1.** Identified absorption lines listed by ion and wavelength. aThe system the absorbing ion belongs to: the Milky Way (MW), the quasar (QSO), or galaxy 1 or 2 (gal1 or gal2). bThe equivalent width of the full absorption system associated with this transition. cThe central wavelength of the full absorbing structure.

| Ion a | System b | Equivalent width c (Å) |
|-------|----------|------------------------|
| Si IV 1393 | MW | 0.40 |
| Si IV 1402 | MW | 0.36 |
| *C II 1036 | gal2 | 2.60 |
| +Fe II 1144 | +gal1 | |
| +O VI 1037 | +gal2 | |
| C III 977 | QSO outflow | 0.11 |
| v ~ -720 to -570 km s⁻¹ | |
| C III 977 | QSO outflow | 0.06 |
| v ~ -480 to -390 km s⁻¹ | |
| *S IV 1062 | gal2 | 0.06 |
| +Si II 989 | +QSO | |
| +N III 989 | +QSO | |
| *Fe II 1063 | gal2 | 0.08 |
| +Si II 989 | +QSO | |
| +N III 989 | +QSO | |
| *Fe II 1096 | gal2 | 0.06 |
| +Ly-α | +Ly-α forest | |
| *S I 1473 | MW | 0.50 |
| +S III 1012 | +QSO | |
| O VI 1031 | QSO outflow | 1.41 |
| v ~ -1080 to -180 km s⁻¹ | |
| O VI 1037 | QSO outflow | 1.70 |
| v ~ -1160 to -170 km s⁻¹ | |
| Si II 1526 | MW | 0.80 |
| C IV 1548 | MW | 0.39 |
| C IV 1550 | MW | 0.20 |
| N II 1083 | QSO | 0.14 |
| Fe II 1068 | MW | 0.52 |
| C I 1656 | MW | 0.04 |

**Table 2.** Ly-α absorption systems in the spectrum. aThe approximate central wavelength of the absorbing structure. bThe equivalent width of the full absorbing structure. cThe central wavelength of each component in the absorbing structure. dThe log of the best-fit column density for each absorption component. Lines that are later identified as broad Ly-α absorbers (BLAs) are marked in bold (see §4.4).

| System | Equivalent width d (log cm⁻²) |
|--------|-----------------------------|
| 1215 Å | 1396.7, 0.17, 0.14893, 13.59 |
| 1409.9, 0.12, 0.15974, 13.41 |
| 1411.1, 0.75, 0.16054, 14.35 |
| +O VI 1037 | 1412.7, 0.11, 0.16209, 13.32 |
| 1415.3, 0.20, 0.16405, 13.48 |
| 1450.5, 0.71, 0.19317, 14.59 |
| 1453.1, 0.36, 0.19530, 14.34 |
| 1457.2, 0.15, 0.19863, 13.43 |
| 1459.2, 0.13, 0.20029, 13.40 |
| 1460.0, 0.54, 0.20586, 14.08 |
| 1467.4, 0.45, 0.20709, 13.92 |
| 1475.5, 0.24, 0.21372, 13.71 |
| 1476.4, 0.33, 0.21445, 13.82 |
| 1485.0, 0.05, 0.22151, 12.98 |
| 1486.7, 0.45, 0.22292, 14.94 |
| 1552.6, 0.70, 0.27688, 13.21 |
| 1556.3, 0.31, 0.28014, 13.83 |
| 1626.0, 0.85, 0.33721, 14.35 |
| 1629.1, 0.16, 0.34011, 13.42 |
| 1638.9, 0.25, 0.34812, 13.73 |
| 1641.6, 0.12, 0.35037, 13.40 |
| 1671.8, 2.05, 0.37440, 14.92 |
| 1675.5, 0.70, 0.37485, 13.41 |
| 1677.4, 0.16, 0.37544, 14.66 |
| 1700.8, 0.43, 0.39094, 14.44 |
| 1706.9, 0.11, 0.40406, 13.28 |
| 1718.9, 0.61, 0.41398, 14.57 |
| 1724.7, 0.16, 0.41869, 13.43 |
| 1727.2, 0.51, 0.42059, 13.77 |
| 0.42105, 13.45 |
Figure 7. The normalized spectrum centered on absorption lines in the CGM of the first galaxy at $z = 0.22784$ as a function of velocity relative to the galaxy systemic velocity (black). Each panel shows a different absorption line, as labeled. The best-fit Voigt profiles for each absorption line are overplotted in red, and the individual absorption components are plotted in blue. For O VI $\lambda 1031, \lambda 1037$ Å, we show the COS-Halos spectrum and the fit to absorption in this spectrum, because our new spectrum that is the focus of this work does not cover the O VI doublet at the redshift of galaxy 1.

Figure 8. The normalized spectrum centered on absorption lines in the CGM of the second galaxy at $z = 0.35569$ as a function of velocity relative to the galaxy systemic velocity (black). Each panel shows a different absorption line, as labeled. The best-fit Voigt profiles for each absorption system are overplotted in red, and the individual absorption components are plotted in blue.

3 VOIGT PROFILE FITTING

We use the software VPFit to fit multicomponent Voigt profiles to the absorption lines identified in §2.1 as belonging to the CGM of galaxies 1 and 2. We obtain velocity centroids relative to the galaxy systemic velocity $v_{\text{sys}}$, Doppler broadening parameters $b_{\text{eff}}$, and column densities $\log N$ for each absorbing component of each ion. Tables 3 and 4 list the parameters of the best-fit absorption profiles for all absorption components in the CGM of galaxies 1 and 2, respectively.

Separate transitions of the same ion are fit simultaneously, except for where there is significant contamination of a line. For galaxy 1, only the N V $\lambda 1242$ Å transition is fit, then the fit is applied to the $\lambda 1238$ Å transition. This same process is also applied to the COS-Halos spectrum at the O VI lines; the $\lambda 1031$ Å transition is fit and that fit is applied to the $\lambda 1037$ Å transition. For galaxy 2, the O VI $\lambda 1037$ Å transition is also contaminated, so the fit is only performed to the $\lambda 1031$ Å transition as well. However, both transitions for N V are free of contamination for galaxy 2, so they are fit simultaneously. All Si II transitions are fit simultaneously for galaxy 1, but only the $\lambda 1193, \lambda 1260$ Å transitions for Si II are fit simultaneously for galaxy 2, and then the fits are applied to the other Si II transitions. For galaxy 1, both Si IV transitions are fit simultaneously.

The reduced $\chi^2$ values for each fit indicate that the fits are acceptable, but that the errors on the spectrum may be over-estimated, possibly due to correlated errors between each pixel in the spectrum. The errors on the fitted velocity centroids are small, at the level of $1 - 3$ km s$^{-1}$ for clearly separated absorption components, increasing to $30 - 40$ km s$^{-1}$ for systems with significant overlap between the absorbing components, such as galaxy 2’s O VI absorption. The errors on the Doppler parameter are somewhat larger, $2 - 4$ km s$^{-1}$ for most components, and increasing to $10 - 20$ km s$^{-1}$ for the O VI system. With the exception of galaxy 2’s O I absorption (0.15 dex error on one component), O VI absorption (errors of 0.19 and 0.22 dex on the two ambiguous intermediate velocity components), and Si III (0.40 and
### Table 3

The best-fit values for each component of each ion detected in absorption in the CGM of galaxy 1, as determined by VPFit.

- **Ion:** Name of the ion and transition.
- **EW (Å):** Equivalent width of the multi-component best-fit absorption.
- **v$_{cen}$ (km s$^{-1}$):** Doppler centroid of absorption relative to galaxy systemic velocity.
- **b$_{eff}$ (km s$^{-1}$):** Doppler broadening width of the absorption component.
- **log N (cm$^{-2}$):** Log of the column density of the absorbing component.
- **$\chi^2$:** The reduced $\chi^2$ of the multicomponent best fit for each ion, listed in the same row as the first component.
- **log N (cm$^{-2}$):** Log of the column density of this component determined by COS-Halos. Blank entries indicate no measurement was made, while "" symbols indicate the same fitting parameters for multiple transitions of the same ion.

| Ion  | EW (Å) | v$_{cen}$ (km s$^{-1}$) | b$_{eff}$ (km s$^{-1}$) | log N (cm$^{-2}$) | $\chi^2$ | COS-Halos v$_{cen}$ (km s$^{-1}$) | COS-Halos b (km s$^{-1}$) | COS-Halos log N (cm$^{-2}$) |
|------|--------|------------------------|-------------------------|------------------|---------|---------------------------------|--------------------------|---------------------------|
| H I 1215 | 1.34  | $-279.2 \pm 1.9$       | $38.5 \pm 2.8$         | $13.28 \pm 0.02$ | 0.60    |                                 |                          |                           |
| H I 1025 | 1.65  | $-53.4 \pm 1.2$       | $20.6 \pm 1.6$         | $12.79 \pm 0.03$ | 0.91    |                                 |                          |                           |
| N II 1084 | 0.30  | $10.4 \pm 1.8$        | $26.6 \pm 2.7$         | $14.22 \pm 0.03$ | 1.68    | $20.9 \pm 4.0$                  | $27.6 \pm 6.4$           | $14.33 \pm 0.07$          |
| N V 1238 | 0.14  | $-32.8 \pm 2.6$       | $31.5 \pm 4.0$         | $13.81 \pm 0.04$ | 0.58    |                                 |                          |                           |
| N V 1242 | 0.07  | "                      | "                      | "                | "       |                                 |                          |                           |
| O VI 1031 | 0.70  | $0.42$                | $-27.2 \pm 6.0$        | $49.4 \pm 5.1$   | 14.77   | $70.7 \pm 18.6$                 | $68.2 \pm 16.3$          | $14.44 \pm 0.14$          |
| Si II 1190 | 0.03  | $-53.4 \pm 1.2$       | $20.6 \pm 1.6$         | $12.79 \pm 0.03$ | 0.91    |                                 |                          |                           |
| Si II 1193 | 0.05  | "                      | "                      | "                | "       |                                 |                          |                           |
| Si II 1260 | 0.10  | "                      | "                      | "                | "       |                                 |                          |                           |
| Si III 1206 | 0.36  | $-54.2 \pm 1.0$       | $21.5 \pm 1.4$         | $13.22 \pm 0.02$ | 0.58    | $-45.0 \pm 2.6$                | $20.0 \pm 4.2$           | $13.20 \pm 0.08$          |
| Si IV 1393 | 0.22  | "                      | "                      | "                | "       |                                 |                          |                           |
| Si IV 1402 | 0.13  | "                      | "                      | "                | "       |                                 |                          |                           |

### Table 4

Same as Table 3 but for the absorption systems in the CGM of galaxy 2.
tion, as determined by VPFit. The column densities of each component of the best-fit absorption as determined by VPFit. The column densities of each component of the absorption reported by COS-Halos. Blank entries indicate no measurement was made, while " symbols indicate the same fit parameters for different transitions of the same ion.

| Ion         | log \(N_{\text{tot}}\) (cm\(^{-2}\)) | COS-Halos log \(N_{\text{tot}}\) (cm\(^{-2}\)) |
|-------------|--------------------------------------|-----------------------------------------------|
| H I 1215    | 14.99 ± 0.03                         | 14.02 ± 0.10                                  |
| C II 1334   | 14.36 ± 0.02                         | 14.02 ± 0.10                                  |
| N V 1238    | 13.81 ± 0.04                         | 14.02 ± 0.10                                  |
| N V 1242    |                                       | 14.02 ± 0.10                                  |
| O VI 1031   |                                       | 14.93 ± 0.07                                  |
| Si II 1190  | 12.79 ± 0.03                         | 13.30 ± 0.07                                  |
| Si II 1193  | "                                    | 13.30 ± 0.07                                  |
| Si II 1260  | "                                    | 13.30 ± 0.07                                  |
| Si III 1206 | 13.36 ± 0.02                         | 13.30 ± 0.07                                  |
| Si IV 1393  | 13.44 ± 0.03                         | 13.30 ± 0.07                                  |
| Si IV 1402  | "                                    | 13.30 ± 0.07                                  |

Table 5. The sum of the column densities of each component of each ion’s absorption. a Name of the ion and transition. b Sum of the column densities of each component of the best-fit absorption, as determined by VPFit. c Sum of the column densities of each component of the absorption reported by COS-Halos. Blank entries indicate no measurement was made, while " symbols indicate the same fit parameters for different transitions of the same ion.

0.82 dex errors on two largest velocity components), the errors on the log column density for each component are only 0.02 – 0.07 dex.

In most cases, the number of components to fit in the multicomponent absorption profiles is easily determined by eye. The two exceptions are galaxy 2’s O VI and Si III, where the O VI absorption could be 3 or more components, and the saturated component in Si III between ~25 and 150 km s\(^{-1}\) could be decomposed into two components that align with the two components seen in the Si II transitions at 10 and 90 km s\(^{-1}\). Both of these transitions were previously observed in the COS-Halos spectrum, so we use the same number of components used there to facilitate comparison: four components for O VI and three for Si III, which assumes the large saturated component is a single component, and is not decomposed into two.

Tables 5 and 6 report the sum of component column densities for each transition, for galaxies 1 and 2, respectively. Again, the column densities with the largest errors are those for the transitions where we detect saturated absorption: H I and Si III for galaxy 2. Galaxy 2 has larger column densities than galaxy 1 for every ion that is detected in the CGM of both galaxies, with the exception of N V, which is 0.42 dex higher in galaxy 1 than in galaxy 2. Galaxy 2’s H I and Si III are larger than galaxy 1’s by 1.55 dex and 1.91 dex, respectively. Galaxy 2 has a larger Si II column density than galaxy 1 by 1.22 dex.

In general, galaxy 2 has higher column densities than galaxy 1. Without detailed ionization or CGM modeling, we cannot definitively comment on the origin of the higher column densities. However, galaxy 2 has a lower impact parameter to the spectrum than galaxy 1 and has a higher stellar mass, so if there is a trend of decreasing column densities with increasing impact parameter or a trend of increasing CGM column density with increasing stellar mass of the host galaxy (both trends are suggested across many studies, see Tumlinson et al. 2017 for a compilation), then we see these trends in our spectrum as well. More detailed modeling, including ionization modeling to determine the densities and temperatures of the gas traced by the metal lines with various ionization energies, will be presented in a forthcoming paper.

3.1 Comparison to Previous Fits

In Tables 5 and 6, the results from fitting these absorption lines as determined by the COS-Halos study are included, where available. Many of the best-fit velocity centroids we find are shifted ~ 10 km s\(^{-1}\) blueward of the COS-Halos reported \(v_{\text{cen}}\), because we use the galaxy redshifts with five significant digits reported by Tumlinson et al. (2013) while the primary COS-Halos fits use the galaxy redshifts with four significant digits reported by Werk et al. (2012). The values of the Doppler parameter \(b_{\text{tot}}\) we find are similar to those found in the COS-Halos study, with the largest differences between our measurements and the COS-Halos measurements occurring for the saturated or otherwise ambiguous absorption components with the largest errors.

Many of the column densities we recover are similar to those reported by COS-Halos, both the column densities of individual absorption components and the summed column density across all components. We find a somewhat lower column density for Si III in galaxy 2’s CGM than that found by COS-Halos, by 1.07 dex. Si III is clearly heavily saturated in both the COS-Halos spectrum (Tumlinson et al. 2011) and ours, which greatly increases the errors on the derived column density.

Despite some differences in the velocity, width, and strength of the multiple components of O VI absorption in galaxy 2’s CGM between our fits and COS-Halos, the summed column densities across all components for both studies match quite well. COS-Halos reports a detection of a third N II absorption component at ~ 180 km s\(^{-1}\) in galaxy 2’s CGM, which was perhaps due to a spurious fluctuation in the low signal-to-noise COS-Halos spectrum. With our higher signal-to-noise spectrum, it is clear that there is no N II absorption at this velocity (see Figure 5).

In general, the errors on our derived absorption parameters are smaller than those reported by COS-Halos, due to our higher signal-to-noise spectrum. For galaxy 1, which has fewer saturated or multicomponent lines, our errors on \(v_{\text{cen}}\) are ~ 1/2 those on COS-Halos’ \(v_{\text{cen}}\), the errors on \(b\) are ~ 1/2 – 2/3 those of COS-Halos, and the errors on log \(N\) are 0.06 – 0.13 dex smaller than COS-Halos. Galaxy 2 has more...
saturated or extended multicomponent absorption where the separation of the components is not clear, such as the O VI absorption, where our errors on the fitted parameters are similar to those reported by COS-Halos. Our fits perform much better than COS-Halos for galaxy 2’s Si II and Si III, as we are able to get fairly good fits despite the saturation of these absorption lines. In these cases, our errors on $v_{\text{cen}}$ and $b$ are a factor of $5 - 10$ smaller than COS-Halos. Our errors on the column densities are $0.15 - 0.5$ dex smaller than COS-Halos reports for Si II and some components of Si III, but are roughly equivalent to the COS-Halos column density errors for certain saturated or ambiguous components. Smaller errors on velocity components and the ability to resolve velocity components separately are crucial to understanding the kinematics of gas, and thus the ionization process and gas properties, in the CGM. A high signal-to-noise spectrum, like we present here, is necessary to obtain this precision.

4 DISCUSSION

4.1 Ionization Processes

4.1.1 Galaxy 1 at $z = 0.22784$

There is absorption in Si II, Si III, and Si IV in the CGM of galaxy 1 at similar velocities, indicating these three ions arise in comoving, and possibly cospatial, gas. The presence of multiple low ionization states of the same element in the same cloud of gas indicates the gas is photoionized. Without detailed photoionization modeling, which will be performed in a forthcoming paper, we cannot speculate on the density or ionization parameter, but we can rule out collisional ionization as the ionization process giving rise to observed ionization states of silicon.

The most-positive velocity component of the O VI absorption at $\sim 70$ km s$^{-1}$ is roughly aligned with one of the resolved velocity components of the H I absorption at $\sim 114$ km s$^{-1}$. If these two absorption components trace the same gas at the same temperature, then the velocity width of the H I component should be consistent with the temperature inferred from the O VI absorption component. If the O VI-absorbing gas were in CIE, its temperature would be expected to be $\sim 10^{6.5}$ K, which would lead to a thermal broadening of H I of $b_{\text{th}} \approx 70$ km s$^{-1}$. The most closely aligned H I component to this O VI component has a width of $b_{\text{th}} = 11$ km s$^{-1}$, so if the H I and O VI absorption components trace the same gas, it cannot be in CIE at the expected temperature.

4.1.2 Galaxy 2 at $z = 0.35569$

The strong lines of Si IV fall outside the extent of our spectrum for galaxy 2, but we see that absorption in Si II and Si III lines are comoving and possibly cospatial, similar to galaxy 1. The presence of multiple low-ionization state lines in galaxy 2’s CGM that may trace the same gas indicates the gas may be photoionized, as we saw in galaxy 1 above. Again, detailed photoionization modeling is necessary to derive densities and ionization parameters.

We do not detect multiple absorption components in H I $\lambda 1215$ to compare to the resolved absorption components in other ions, but there is one resolved component in H I $\lambda 1025$ at $\sim 190$ km s$^{-1}$ that aligns with the most-positive velocity component of the O VI absorption at $\sim 197$ km s$^{-1}$. If the comoving gas traced by both this H I component and this O VI component is cospatial, in CIE, and at a constant temperature, then again we would expect the thermal broadening of the H I component to be consistent with the temperature of $\sim 10^{6.5}$ K. Similarly to galaxy 1, the H I component that aligns with the O VI component in galaxy 2’s CGM has a Doppler broadening width too small to be produced by high-temperature gas: $b_{\text{th}} \sim 24$ km s$^{-1}$. We conclude that if the gas producing the absorption components in H I and O VI at $\sim 190$ km s$^{-1}$ are cospatial, this gas cannot be in CIE.

4.2 N V and O VI

The ratio of N V to O VI column densities can reveal the processes that ionized these elements, and determine whether they are in ionization equilibrium. Indebetouw & Shull (2004) present a list of various non-equilibrium ionization processes collected from the literature and the log($N_{\text{NV}}/N_{\text{OVI}}$) ratios expected from each process. Here, we calculate the N V to O VI column density ratios for our two galaxies’ CGM and compare to the ratios in Indebetouw & Shull (2004) to estimate the ionization process for these high ions. We also compare to Wakker et al. (2012) and Bordoloi et al. (2017) for more recent determinations of the high-ionization state metal column densities expected from a flow of radiatively cooling gas, and to other measured values of the log($N_{\text{NV}}/N_{\text{OVI}}$) ratio in the Milky Way halo (Wakker et al. 2012), other low-$z$ galaxies (Werk et al. 2013), low-$z$ intergalactic medium absorbers (Burchett et al. 2015), high-$z$ galaxies (Lehner et al. 2014), and high-$z$ damped Ly-$\alpha$ absorbers (Fox et al. 2007).

4.2.1 Galaxy 1 at $z = 0.22784$

Our spectrum does not extend to the wavelengths of the O VI $\lambda 1031, \lambda 1037$ Å transitions at the redshift of this galaxy, but the previously-obtained COS-Halos spectrum does (Werk et al. 2013). In Figure 9, we overplot the N V absorption from our spectrum at $\lambda 1242$ Å and the O VI absorption from the COS-Halos spectrum at $\lambda 1031$ Å to show that while the absorption of each ion has a different structure, the N V absorption aligns well with the most-negative velocity and strongest O VI absorption component. We calculate the ratio of the column densities for each absorption component in O VI, using the $N_{\text{NV}} \lesssim 12.7$ cm$^{-2}$ detection limit of N V within this region of our spectrum to calculate an upper limit on the ratio for the most-positive velocity O VI absorption component. We find the N V upper limit column density by using VP Fit to try to fit an N V line to what appears to be a flat part of the spectrum. While there is contamination in the spectrum near N V $\lambda 1242$ Å at the velocity that would align with the second O VI absorption component, there is no absorption at this velocity at the location of N V $\lambda 1238$ Å so we consider this a non-detection and use the detection limit to place a limit on log($N_{\text{NV}}/N_{\text{OVI}}$). Note that because the COS-Halos spectrum has a different signal-to-noise ratio than our spectrum, the N V to O VI ratio may

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have a systematic error not captured by the reported error bar due to taking a ratio between two different spectra.

We find a detected column density for N V of log $N_{NV} = 13.81 \pm 0.04$ and a column density for the aligned component of O VI of log $N_{OVI} = 14.77 \pm 0.08$. The log ratio of the column densities is then log($N_{NV}/N_{OVI}) = -0.96 \pm 0.09$. The log-ratio of the column densities for the O VI component that is non-detected at a similar velocity in N V is log($N_{NV}/N_{OVI}) \lesssim -1.74 \pm 0.14$. Figure 11 reproduces Figure 1 from Indebetouw & Shull (2004), with the vertical red line with shading noting the detected value of log($N_{NV}/N_{OVI})$ and its error for galaxy 1. The non-detection is plotted only in the bottom panel as an open red circle with the length of the arrow indicating the error. The detection line passes through both the conductive heating (of spherical clouds in a hot media: Boehringer & Hartquist 1987) and the turbulent mixing regimes (in the interstellar medium at intermediate temperatures: Slavin et al. 1993), crosses and stars, respectively, as reported by Indebetouw & Shull (2004). Without a measurement for $N_{CIV}$, we cannot constrain which process ionizes N V and O VI. Neither our spectrum nor the previously-measured COS-Halos spectrum cover the C IV transitions at 1548 and 1550 Å for either galaxy. The non-detection value does not correlate with any regime collected by Indebetouw & Shull (2004), but does align with some upper limit detections from other systems (see 4.2.2). The difference in the values of the N V to O VI ratio between the detected and non-detected components may indicate that there are multiple ionization processes for N V and O VI within the same halo, but we cannot definitively declare this due to the large amount of blending near both lines of the N V doublet that may be hiding a second absorption component that aligns with the second O VI absorption component.

Walker et al. (2012) find that a radiatively cooling flow model can produce a ratio log($N_{NV}/N_{OVI}) \sim -0.9$ if the flow is isochoric (i.e. if the flow is not constrained by external pressure from a hot halo) and includes photoionization of the cool gas by emission from the hot gas, for a flow velocity of $\sim 60$ km s$^{-1}$. Assuming the sightline is parallel to the direction of the flow (see their Figure 15). Thus, the N V-O VI column density ratio for galaxy 1 could be produced by a cooling flow of intermediate speed, even though the ratio is somewhat higher than suggested for a radiatively cooling flow from Indebetouw & Shull (2004). In Figure 11, we plot the one detected N V component’s ratio as a vertical orange dashed line with shading to indicate the error on this ratio, and the three limits are plotted only in the bottom panel as open orange circles with left-pointing arrows, where the length of the arrow indicates the error on the ratio, and the three limits are plotted only in the bottom panel as open orange circles with left-pointing arrows, where the length of the arrow indicates the error on the ratio. The radiatively cooling flow model reported by Indebetouw & Shull (2004) was calculated by Shapiro & Benjamin (1991) for a Galactic fountain with flow velocity 100 km s$^{-1}$ and external photoionization. Indebetouw & Shull (2004) also find a radiatively cooling flow can be responsible for our measured values of log($N_{NV} \sim 13.8$ and log($N_{OVI} \sim 14.8$, but the velocity required for the flow is faster, $\sim 200$ km s$^{-1}$. Their model also constrains the temperature of the cooling gas to $\sim 10^5$–$5.5$ K (see their Figure 5).

4.2.2 Galaxy 2 at $z = 0.35569$

Our spectrum covers both the N V and O VI transitions at the redshift of galaxy 2. In Figure 10, we overplot the N V A1238 Å (the stronger of the N V doublet lines, but we fit both of them simultaneously) and O VI A1031 Å (the only part of the O VI doublet that is not contaminated, so it is fit alone) absorption in velocity space from our spectrum, along with the best multi-component fits. While O VI has extended, multi-component absorption at a wide range of velocities, we detect weak N V absorption in only a single component at a single velocity that aligns well with the $-100$ km s$^{-1}$ component of the O VI absorption, which is the strongest component. The N V absorption that aligns with the other three O VI absorption components, if present, may be too weak for us to detect. We calculate log($N_{NV}/N_{OVI})$ for all four components of the O VI absorption, but can only place upper limits on log($N_{NV}$ for the three components that do not align with any detected N V absorption. Our detection limit for N V absorption, found by fitting a VP Fit profile to a place in the spectrum near N V absorption and only noise, is log($N_{NV} \lesssim 13.2$.

For the one O VI component with aligned N V detected absorption, we find log($N_{NV}/N_{OVI}) = -1.08 \pm 0.06$. For the other three O VI components at $-25$, 111, and 197 km s$^{-1}$, we place limits of log($N_{NV}/N_{OVI}) \lesssim -1.33 \pm 0.19$, $\lesssim -1.30 \pm 0.22$, and $\lesssim -0.93 \pm 0.04$, respectively. In Figure 11 we plot the one detected N V component’s ratio as a vertical orange dashed line with shading to indicate the error on this ratio, and the three limits are plotted only in the bottom panel as open orange circles with left-pointing arrows, where the length of the arrow indicates the error on the non-detections. Without a measurement of C IV absorption, the models reported by Indebetouw & Shull (2004) cannot definitively say which non-equilibrium ionization process produces the N V and O VI gas, but the detection and most of the limits on the N V to O VI column density ratio for galaxy 2 are consistent with either radiative cooling or conductive heating. One of the limits is marginally consistent with turbulent mixing, as well. It seems unlikely that N V and O VI are produced in CIE. The variety of values for the N V to O VI ratio indicates that multiple ionization processes are taking place in the same halo at different velocities, however, the spread in the N V to O VI ratio between

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the different components is not much larger than the spread in this ratio from a single type of non-equilibrium ionization. For example, the extent of the radiatively cooling points (triangles) from Indebetouw & Shull (2004) is $\sim 0.2$ dex in the N V to O VI ratio and the spread between all components of galaxy 2’s absorption is $\sim 0.3$ dex. Similar ionization processes could be acting to produce the N V to O VI column density ratios for each absorption component, despite their spread in the value of the ratio.

The radiative cooling flow model of Wakker et al. (2012) produces a column density ratio $\log(N_{\text{NV}}/N_{\text{OVI}}) \lesssim -1.1$ when the velocity of an isochoric flow with photoionization is $\lesssim 30$ km s$^{-1}$, or if the flow is isochoric without photoionization or isobaric with or without photoionization (see their Figure 15). The cooling flow model of Bordoloi et al. (2017) produces $\log(N_{\text{NV}}) \sim 13.4$ and $\log(N_{\text{OVI}}) \sim 14.6$ when the flow has a velocity of $\sim 80$ km s$^{-1}$ and a temperature of $\sim 10^{5.3-5.5}$ K (see their Figure 5). Therefore, the N V and O VI in galaxy 2’s CGM may arise due to a radiatively cooling flow of gas, albeit at a lower velocity than galaxy 1.

4.2.3 Comparison to Other Measurements

In addition to showing our measured values of $\log(N_{\text{NV}}/N_{\text{OVI}})$ and the models collected by Indebetouw & Shull (2004), Figure 11 also shows a collection of $\log(N_{\text{NV}}/N_{\text{OVI}})$ and $\log(N_{\text{CIV}}/N_{\text{OVI}})$ measurements from other studies as the colored points: the CGM of low-$z$, $\sim L_*$ galaxies (dark green squares), some of the measurements of the CGM of high-$z$ galaxies from Lehner et al. (2014) (magenta pentagons), some of the measurements of high-$z$ damped Ly-α absorbers from Fox et al. (2007) (blue circles), and the bulk of the Milky Way halo measurements from Wakker et al. (2012) (cyan hexagons). This is consistent with the findings of Bordoloi et al. (2017) that many of these measurements can be explained by radiatively cooling gas flows, just as we find our measurements can. In the case of those measurements of the CGM near galaxies, like our measurements, the flowing gas may be fueled by galactic winds. High-velocity cooling gas $\gtrsim 500$ km s$^{-1}$ may be hot, fast galactic winds radiatively cooling as they adiabatically expand out of the galaxy (Thompson et al. 2016). Lochhaas et al. (2018) found that fast galactic winds slow down to $\gtrsim 100-200$ km s$^{-1}$ and can radiatively cool after shocking on the CGM gas, consistent with observations of low-velocity cooling gas.

4.3 $dN/dz$ of Ly-α Absorbers

Assuming all unidentified absorption lines in the spectrum are due to intervening Ly-α forest absorbers, we can compare the number of absorbers in our spectrum to the expected number at the spectrum’s redshift. Because we have only a single spectrum, breaking the spectrum up into many redshift chunks would not provide a very accurate comparison to the statistical sample of Ly-α absorbers with redshift, so we break the spectrum into two redshift bins. The spectrum covers Ly-α redshifts from 0.15 to 0.45, which we split into bins from 0.15 to 0.3 and 0.3 to 0.45, and we find 19 Ly-α absorption components in the first bin and 15 in the second. Restricting the column density of absorbers to $N(Ly\alpha) \geq 13$ reduces the number of absorbers in the first bin to 18 and leaves the second bin unchanged, and restricting to $N(Ly\alpha) \geq 14$ reduces the number of absorbers to 6 in each bin. We calculate $dN/dz$ by dividing the number of absorbers by the redshift extent of the bin, $\Delta z = 0.15$. Figure 12 shows our calculated $dN/dz$ for those absorbers with $N(Ly\alpha) \geq 13$ as the solid black lines and for those absorbers with $N(Ly\alpha) \geq 14$ as the black dashed lines. The observed $dN/dz$ of H I absorbers from Danforth et al. (2016) with $N(HI) > 13$ and $N(HI) > 14$ are shown as the circular and square points with error bars, respectively. The number of Ly-α absorbers in our spectrum agrees well with both column density restricted measurements of $dN/dz$ found by Danforth et al. (2016), although we do not observe the trend with redshift seen in the Danforth et al. (2016) data. Given the stochastic nature of counting absorbers in a single spectrum and the fact that none of the absorbers were identified as any other metal absorption lines, we are nonetheless confident that the unidentified absorption in our spectrum is, in fact, Ly-α absorption of intervening systems.

4.4 Broad Ly-α Absorbers

Broad Ly-α absorbers (BLAs) are regions of high column density neutral hydrogen gas with a high temperature $T \sim 10^5$ K that thermally broadens the absorption line. At these temperatures, the fraction of hydrogen in the neutral state is very low, so BLAs are weak and require high signal-to-noise spectra to find. However, they are useful for probing the warm-hot intergalactic medium because the thermal
Figure 11. In the large panel, the log of the ratio of C IV column density to O VI column density vs. the log of the ratio of N V to O VI column densities. Bottom and left panels are reserved for points with a measurement in only one of the two plotted column density ratios, with the exception of our own measured values, which are also plotted in the large panel. Our detected measurements of $\log(N_{\text{NVI}}/N_{\text{OVI}})$ are plotted as vertical lines with shading indicating the error on the measurement: solid red line for galaxy 1 and dashed orange line for galaxy 2. Upper limits from non-detections are plotted as open circular points in only the bottom panel, again red for galaxy 1 and orange for galaxy 2. Black points are reproduced from Figure 1 of Indebetouw & Shull (2004): crosses show regions of column density ratios expected for conductive heating, asterisks show regions of turbulent mixing, triangles show regions of radiative cooling, and the diagonal dotted line in the bottom right shows ratios expected from CIE. Colored points indicate measured values of the column density ratios collated from various other systems: the CGM of low-z, $\sim L_*$, galaxies (dark green squares Werk et al. 2013), high-z damped Ly-\( \alpha \) absorbers (blue circles Fox et al. 2007), low-z intergalactic medium absorbers (light green diamonds Burchett et al. 2015), the CGM of high-z galaxies (magenta pentagons Lehner et al. 2014), and the Milky Way halo (cyan hexagons Wakker et al. 2012). Filled colored points indicate a measurement for both column density ratios, whereas an open colored point indicates a measurement for one column density ratio and a limit for the other.

Broadening is expected to be larger than any non-thermal broadening (Richter et al. 2006) so a clear measurement of the temperature can be made.

We search for potential BLAs by fitting each component of Ly-\( \alpha \) absorption with a Voigt profile using VPFit and identifying any single-component absorber with a Doppler $b_{\text{eff}}$ parameter greater than 40 km s$^{-1}$. These absorbers are marked in bold in Table 2 and Table 7 lists the wavelength at which we find them, their redshift assuming they are Ly-\( \alpha \) lines, their Doppler $b_{\text{eff}}$ parameters, and their column densities.

At a signal-to-noise level of 30, Tepper-García et al. (2012) predict $dN/dz \sim 28 \pm 5$ for simple (single-component) BLAs, using hydrodynamical simulations of the intergalactic medium. We find 9 in our spectrum that covers $\Delta z = 0.3$, giving $dN/dz \sim 30$. Our signal-to-noise ratio is $\sim 25$, so we expect a somewhat lower $dN/dz$ than 28, so we find slightly more BLAs than we expect. However, 3 of the BLAs in our spectrum have a Doppler $b_{\text{eff}}$ parameter within 2 km s$^{-1}$ of the BLA identifying limit of $b_{\text{eff}} \geq 40$ km s$^{-1}$, and the typical errors on $b_{\text{eff}}$ in our fits are $\sim 2 - 4$ km s$^{-1}$. Some of these BLAs may be mis-identified, if their actual $b_{\text{eff}}$ values are smaller than we find, which would reduce our calculated $dN/dz$. Overall, we find a number of BLAs in our spectrum.
that is consistent with the number predicted for our signal-to-noise ratio from hydrodynamical simulations.

The dN/dz of BLAs in our spectrum is also consistent with the numbers found in quasar spectra in observational studies. Richter et al. (2000) and Lehner et al. (2007) both find a dN/dz ~ 20 – 25 and Danforth et al. (2010) find dN/dz = 18 ± 11, all similar to but lower than the BLA dN/dz we measure for our spectrum. However, if we consider that our BLAs with $b_{\text{eff}} > 40$ km s$^{-1}$ may not be correctly identified as broad given the errors on $b_{\text{eff}}$, then we find dN/dz = 20, in accordance with these studies.

None of the BLAs we identify are associated with either galaxy’s CGM probed by our spectrum, so we assume they trace warm-hot gas in the Ly-$\alpha$ forest. Those with the largest column densities log $N_{\text{HI}} \gtrsim 14$ are close to saturated, so may be misidentified as broad absorption. The H I absorption we detect in the CGM of the two galaxies is fully saturated so if there are any BLA components, they are blended with the saturated H I and we cannot separate them out.

5 SUMMARY AND CONCLUSIONS

We have identified and fit absorption lines in a high signal-to-noise HST COS spectrum toward the quasar SDSS J1009+0713, which is located behind the CGM of two galaxies at $z = 0.228$ and $z = 0.356$. We report on the column densities, velocities, and Doppler broadening parameters of the absorption lines in the CGM of each of these galaxies, and show that our high signal-to-noise spectrum allows us to more accurately measure the absorbing gas than in previous, shallower surveys. Our main results are as follows:

(i) We identify new absorption previously not reported in the CGM of both galaxies: weak N V absorption in both galaxies’ CGM, an additional high-velocity component of Si III in galaxy 1’s CGM, and clearer decomposition of O VI absorption component in galaxy 2’s CGM ($\text{§4.2}$).

(ii) We identify new absorption at $z = 0$ corresponding to absorption in the MW’s CGM as well as at $z = 0.456$, corresponding to absorption of gas surrounding the quasar. The newly-identified quasar absorption includes a fast outflow of O VI up to $\sim 1100$ km s$^{-1}$ (Figure 3).

(iii) The different kinematic structure of low- and high-ionization lines in both galaxies’ CGM indicates these ions are produced in different components of the CGM, are not comoving, and likely not cospatial ($\text{§4.1}$).

(iv) Because both galaxies’ CGM exhibit similar absorption structures in multiple ionization state lines of the same element (Si II, Si III, and Si IV), these low-ions are likely photoionized ($\text{§4.3}$). The narrow features of H I absorption that align well in velocity with components of O VI absorption show that the O VI is not in CIE because H I is not observed to be thermally broadened to the expected temperature.

(v) The column density ratios of N V to O VI we find in the CGM of both galaxies are consistent with those predicted by a radiatively cooling flow of gas traveling at $\sim 30 – 80$ km s$^{-1}$, and these column density ratios are also similar to those measured in the CGM of other galaxies as well as in the Milky Way halo. Radiatively cooling gas traveling at this velocity can be produced by fast galactic winds shocking on CGM gas ($\text{.§4.2}$ and Figure 11).

(vi) Different values of the N V to O VI column density ratio within one CGM (as for galaxy 2) indicates that O VI is produced in different ionization processes within the same CGM ($\text{§4.2}$ and Figure 11).

(vii) We identify both Ly-$\alpha$ forest absorption lines and broad Ly-$\alpha$ absorbers with the expected number density from both simulations of the intergalactic medium and observational studies ($\text{§4.3}$ and $\text{§4.4}$).

We have shown that a high signal-to-noise spectrum can improve errors on measured column densities by $\sim 0.1$ dex and improve absorption line velocity centroids and Doppler broadening widths by a factor of $\sim 2$. These precise measurements reduce the uncertainty on ionization process for the high-ionization state metals, such as N V and O VI, which

Figure 12. The redshift evolution of number of Ly-$\alpha$ absorbers in our spectrum as a function of redshift, dN/dz for those absorbers with $N$(Ly-$\alpha$) $\geq 13$ is shown as a black solid line, and dN/dz for those absorbers with $N$(Ly-$\alpha$) $\geq 14$ is shown as a black dashed line. We break our spectrum into two redshift bins, but the number of absorbers in each bin is the same for those absorbers with $N$(Ly-$\alpha$) $\geq 14$. We show, for comparison, the measured dN/dz from Danforth et al. (2016) for absorbers with $N$(HI) $> 13$ and $N$(HI) $> 14$ as circular and square points, respectively, with error bars and connecting lines.

Table 7. Broad Ly-$\alpha$ absorbers in our spectrum, defined as Ly-$\alpha$ absorbers with Doppler $b_{\text{eff}} > 40$ km s$^{-1}$. $^a$Wavelength of the BLA. $^b$Redshift of the absorption. $^c$The Doppler $b_{\text{eff}}$ broadening parameter. $^d$The log of the column density.

| Wavelength $^a$ (Å) | $z^b$ | $b_{\text{eff}}^c$ (km s$^{-1}$) | $\log N_{\text{Ly}}^{d}$ (cm$^{-2}$) |
|---------------------|--------|-----------------------------|----------------------------------|
| 1450.5              | 0.19317| 48.6                        | 14.59                            |
| 1457.2              | 0.19863| 74.9                        | 13.43                            |
| 1466.0              | 0.20586| 81.7                        | 14.08                            |
| 1467.4              | 0.20709| 114.0                       | 13.92                            |
| 1475.5              | 0.21372| 65.1                        | 13.71                            |
| 1476.4              | 0.21445| 64.9                        | 13.82                            |
| 1556.3              | 0.28014| 40.8                        | 13.83                            |
| 1629.1              | 0.34011| 41.4                        | 13.42                            |
| 1724.7              | 0.41869| 41.9                        | 13.43                            |

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Lochhaas et al. have many potential ionization processes that are difficult to distinguish between. Such deep spectra are crucial for uncovering weak but very diagnostically useful absorbers, such as $\text{N V}$, as well as for allowing more precise kinematic modeling of absorption systems. We will report on more detailed ionization modeling of the absorption lines in this spectrum in a future paper. While broad and shallow surveys give a statistical understanding of the CGM, deep spectra like the one reported in this paper are necessary for accurately measuring and modeling the state of CGM gas. Additional deep spectra will improve our understanding of the gas phases and hydrodynamic processes of the CGM.

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